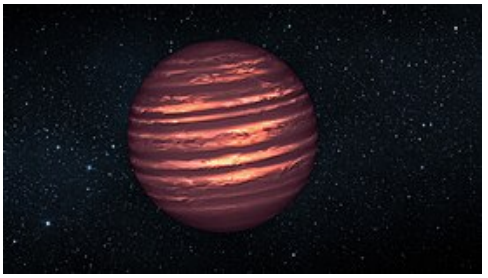
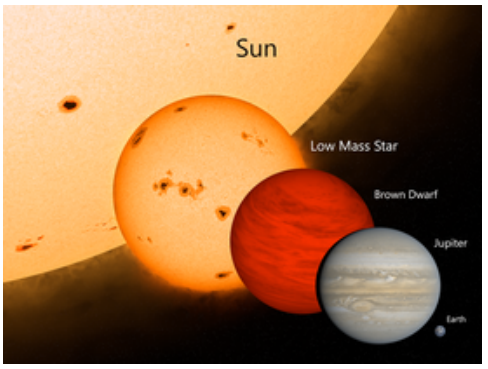
Brown dwarf

Brown dwarfs are substellar objects that have more mass than the biggest gas giant planets, but less than the least massive main-sequence stars. Their mass is approximately 13 to 80 times that of Jupiter (M_J)[2][3]—not big enough to sustain nuclear fusion of ordinary hydrogen (^{1}H) into helium in their cores, but massive enough to emit some light and heat from the fusion of deuterium (^{2}H). The most massive ones (> 65 M_J) can fuse lithium (^{7}Li).[3]



Artist's concept of a T-type brown dwarf



Comparison: most brown dwarfs are slightly larger than Jupiter (15–20%),[1] but are still up to 80 times more massive due to greater density. Image is to scale, with Jupiter's radius being 11 times that of Earth, and the Sun's radius 10 times that of Jupiter.

Astronomers classify self-luminous objects by spectral type, a distinction intimately tied to the surface temperature, and brown dwarfs occupy types M, L, T, and Y.[4][5] As brown dwarfs do not undergo stable hydrogen fusion, they cool down over time, progressively passing through later spectral types as they age.

Their name comes not from the color of light they emit but from their falling between white dwarf stars and "dark" planets in size. To the naked eye, brown dwarfs would appear in different colors depending on their temperature.[4] The warmest ones are possibly orange or red,[6] while cooler brown dwarfs would likely appear magenta or black to the human eye.[4][7] Brown dwarfs may be fully convective, with no layers or chemical differentiation by depth.[8]

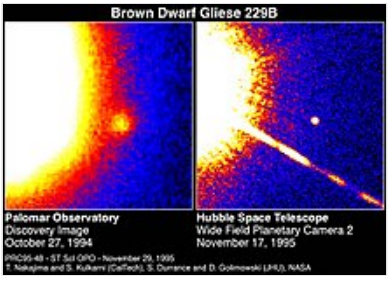
Though their existence was initially theorized in the 1960s, it was not until the mid-1990s that the first unambiguous brown dwarfs were discovered. As brown dwarfs have relatively low surface temperatures, they are not very bright at visible wavelengths, emitting most of their light in the infrared. However, with the advent of more capable infrared detecting devices, thousands of brown dwarfs have been identified. The nearest known brown dwarfs are located in the Luhman 16 system, a binary of L- and T-type brown dwarfs about 6.5 light-years (2.0 parsecs) from the Sun. Luhman 16 is the third closest system to the Sun after Alpha Centauri and Barnard's Star.

History

Early theorizing

Planets, brown dwarfs, stars (not to scale)

The objects now called "brown dwarfs" were theorized by Shiv S. Kumar in the 1960s to exist and were originally called black dwarfs,[9] a classification for dark substellar objects floating freely in space that were not massive enough to sustain hydrogen fusion. However, (a) the term black dwarf was already in use to refer to a cold white dwarf; (b) red dwarfs fuse hydrogen; and (c) these objects may be luminous at visible wavelengths early in their lives. Because of this, alternative names for these objects were proposed, including planetar and substar. In 1975, Jill Tarter suggested the term "brown dwarf", using "brown" as an approximate color.[6][10][11]



The smaller object is Gliese 229B, about 20 to 50 times the mass of Jupiter, orbiting the star Gliese 229. It is in the constellation Lepus, about 19 light-years from Earth.

The term "black dwarf" still refers to a white dwarf that has cooled to the point that it no longer emits significant amounts of light. However, the time required for even the lowest-mass white dwarf to cool to this temperature is calculated to be longer than the current age of the universe; hence such objects are expected to not yet exist.[12]

Early theories concerning the nature of the lowest-mass stars and the hydrogen-burning limit suggested that a population I object with a mass less than 0.07 solar masses ($M_\odot$) or a population II object less than 0.09 $M_\odot$ would never go through normal stellar evolution and would become a completely degenerate star.[13] The first self-consistent calculation of the hydrogen-burning minimum mass confirmed a value between 0.07 and 0.08 solar masses for population I objects.[14][15]

Deuterium fusion

The discovery of deuterium burning down to 0.013 $M_\odot$ (13.6 jupiter mass) and the impact of dust formation in the cool outer atmospheres of brown dwarfs in the late 1980s brought these theories into question. However, such objects were hard to find because they emit almost no visible light. Their strongest emissions are in the infrared (IR) spectrum, and ground-based IR detectors were too imprecise at that time to readily identify any brown dwarfs.

Since then, numerous searches by various methods have sought these objects. These methods included multi-color imaging surveys around field stars, imaging surveys for faint companions of main-sequence dwarfs and white dwarfs, surveys of young star clusters, and radial velocity monitoring for close companions.

GD 165B and class L

For many years, efforts to discover brown dwarfs were fruitless. In 1988, however, a faint companion to the white dwarf star GD 165 was found in an infrared search of white dwarfs. The spectrum of the companion GD 165B was very red and enigmatic, showing none of the features expected of a low-mass red dwarf. It became clear that GD 165B would need to be classified as a much cooler object than the latest **M** dwarfs then known. GD 165B remained unique for almost a decade until the advent of the Two Micron All-Sky Survey (2MASS) in 1997, which discovered many objects with similar colors and spectral features.

Today, GD 165B is recognized as the prototype of a class of objects now called "**L** dwarfs".[16][17]

Although the discovery of the coolest dwarf was highly significant at the time, it was debated whether GD 165B would be classified as a brown dwarf or simply a very-low-mass star, because observationally it is very difficult to distinguish between the two.

Soon after the discovery of GD 165B, other brown-dwarf candidates were reported. Most failed to live up to their candidacy, however, because the absence of lithium showed them to be stellar objects. True stars burn their lithium within a little over 100 Myr, whereas brown dwarfs (which can, confusingly, have temperatures and luminosities similar to true stars) will not. Hence, the detection of lithium in the atmosphere of an object older than 100 Myr ensures that it is a brown dwarf.

Gliese 229B and class T

The first class "T" brown dwarf was discovered in 1994 by Caltech astronomers Shrinivas Kulkarni, Tadashi Nakajima, Keith Matthews and Rebecca Oppenheimer,[18] and Johns Hopkins scientists Samuel T. Durrance and David Golimowski. It was confirmed in 1995 as a substellar companion to Gliese 229. Gliese 229b is one of the first two instances of clear evidence for a brown dwarf, along with Teide 1. Confirmed in 1995, both were identified by the presence of the 670.8 nm lithium line. The latter was found to have a temperature and luminosity well below the stellar range.

Its near-infrared spectrum clearly exhibited a methane absorption band at 2 micrometres, a feature that had previously only been observed in the atmospheres of giant planets and that of Saturn's moon Titan. Methane absorption is not expected at any temperature of a main-sequence star. This discovery helped to establish yet another spectral class even cooler than **L** dwarfs, known as "**T** dwarfs", for which Gliese 229B is the prototype.

Teide 1 and class M

The first confirmed class "M" brown dwarf was discovered by Spanish astrophysicists Rafael Rebolo (head of the team), María Rosa Zapatero-Osorio, and Eduardo L. Martín in 1994.[19] This object, found in the Pleiades open cluster, received the name Teide 1. The discovery article was submitted to *Nature* in May 1995, and published on 14 September 1995.[20][21] *Nature* highlighted "Brown dwarfs discovered, official" in the front page of that issue.

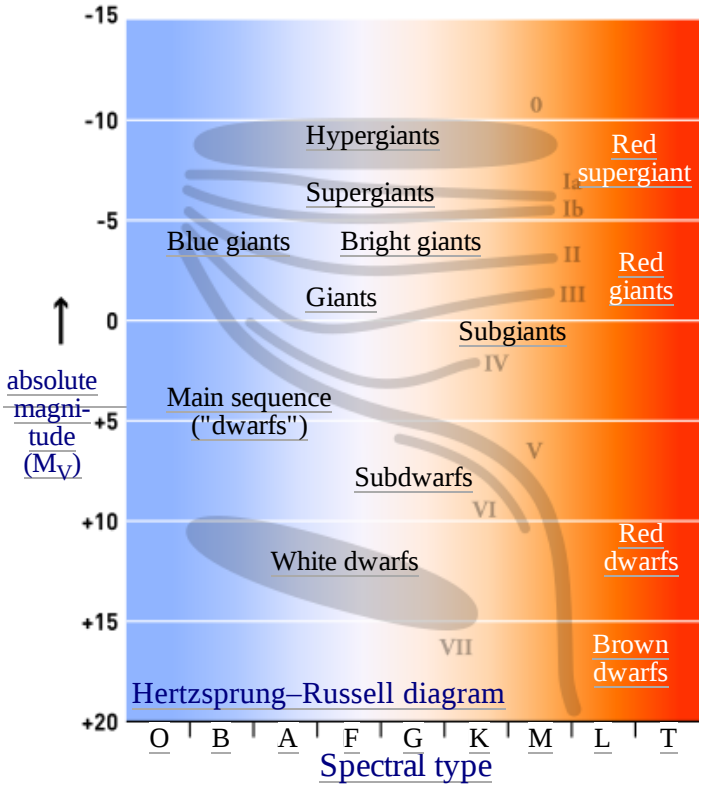
Teide 1 was discovered in images collected by the IAC team on 6 January 1994 using the 80 cm telescope (IAC 80) at Teide Observatory and its spectrum was first recorded in December 1994 using the 4.2 m William Herschel Telescope at Roque de los Muchachos Observatory (La Palma). The distance, chemical composition, and age of Teide 1 could be established because of its membership in the young Pleiades star cluster. Using the most advanced stellar and substellar evolution models at that moment, the team estimated for Teide 1 a mass of 55 ± 15 M_J,[22] which is below the stellar-mass limit. The object became a reference in subsequent young brown dwarf related works.

In theory, a brown dwarf below 65 M_J is unable to burn lithium by thermonuclear fusion at any time during its evolution. This fact is one of the lithium test principles used to judge the substellar nature of low-luminosity and low-surface-temperature astronomical bodies.

High-quality spectral data acquired by the Keck 1 telescope in November 1995 showed that Teide 1 still had the initial lithium abundance of the original molecular cloud from which Pleiades stars formed, proving the lack of thermonuclear fusion in its core. These observations confirmed that Teide 1 is a brown dwarf, as well as the efficiency of the spectroscopic lithium test.

For some time, Teide 1 was the smallest-known object outside the Solar System that had been identified by direct observation. Since then, over 1,800 brown dwarfs have been identified,[23] even some very close to Earth like Epsilon Indi Ba and Bb, a pair of brown dwarfs gravitationally bound to a Sun-like star 12 light-years from the Sun,[24] and Luhman 16, a binary system of brown dwarfs at 6.5 light-years from the Sun.

Theory



The standard mechanism for star birth is through the gravitational collapse of a cold interstellar cloud of gas and dust. As the cloud contracts it heats due to the Kelvin–Helmholtz mechanism. Early in the process the contracting gas quickly radiates away much of the energy, allowing the collapse to continue. Eventually, the central region becomes sufficiently dense to trap radiation. Consequently, the central temperature and density of the collapsed cloud increases dramatically with time, slowing the contraction, until the conditions are hot and dense enough for thermonuclear reactions to occur in the core of the protostar. For most stars, gas and radiation pressure generated by the thermonuclear fusion reactions within the core of the star will support it against any further gravitational contraction. Hydrostatic equilibrium is reached and the star will spend most of its lifetime fusing hydrogen into helium as a main-sequence star.

If, however, the initial[25] mass of the protostar is less than about 0.08 $M_\odot$,[26] normal hydrogen thermonuclear fusion reactions will not ignite in the core. Gravitational contraction does not heat the small protostar very effectively, and before the temperature in the core can increase enough to trigger fusion, the density reaches the point where electrons become closely packed enough to create quantum electron degeneracy pressure. According to the brown dwarf interior models, typical conditions in the core for density, temperature and pressure are expected to be the following:

- $10\,\mathrm{g/cm^3} \lesssim \rho_c \lesssim 10^3\,\mathrm{g/cm^3}$
- $T_c \lesssim 3 \times 10^6\,\mathrm{K}$

- $P_c \sim 10^5$ Mbar.

This means that the protostar is not massive enough and not dense enough to ever reach the conditions needed to sustain hydrogen fusion. The infalling matter is prevented, by electron degeneracy pressure, from reaching the densities and pressures needed.

Further gravitational contraction is prevented and the result is a brown dwarf that simply cools off by radiating away its internal thermal energy. Note that, in principle, it is possible for a brown dwarf to slowly accrete mass above the hydrogen burning limit without initiating hydrogen fusion. This could happen via mass transfer in a binary brown dwarf system.[25]

High-mass brown dwarfs versus low-mass stars

Lithium is generally present in brown dwarfs and not in low-mass stars. Stars, which reach the high temperature necessary for fusing hydrogen, rapidly deplete their lithium. Fusion of lithium-7 and a proton occurs producing two helium-4 nuclei. The temperature necessary for this reaction is just below that necessary for hydrogen fusion. Convection in low-mass stars ensures that lithium in the whole volume of the star is eventually depleted. Therefore, the presence of the lithium spectral line in a candidate brown dwarf is a strong indicator that it is indeed a substellar object.

The lithium test

The use of lithium to distinguish candidate brown dwarfs from low-mass stars is commonly referred to as the **lithium test**, and was pioneered by Rafael Rebolo, Eduardo Martín and Antonio Magazzu. However, lithium is also seen in very young stars, which have not yet had enough time to burn it all.

Heavier stars, like the Sun, can also retain lithium in their outer layers, which never get hot enough to fuse lithium, and whose convective layer does not mix with the core where the lithium would be rapidly depleted. Those larger stars are easily distinguishable from brown dwarfs by their size and luminosity.

Conversely, brown dwarfs at the high end of their mass range can be hot enough to deplete their lithium when they are young. Dwarfs of mass greater than 65 M_J can burn their lithium by the time they are half a billion years old,[27] thus the lithium test is not perfect.

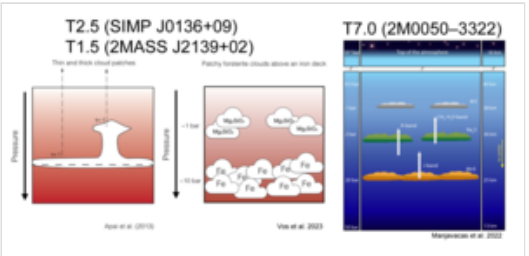
Atmospheric methane

Unlike stars, older brown dwarfs are sometimes cool enough that, over very long periods of time, their atmospheres can gather observable quantities of methane, which cannot form in hotter objects. Dwarfs confirmed in this fashion include Gliese 229B.

Iron, silicate and sulfide clouds

Main-sequence stars cool, but eventually reach a minimum bolometric luminosity that they can sustain through steady fusion. This varies from star to star, but is generally at least 0.01% that of the Sun. Brown dwarfs cool and darken steadily over their lifetimes; sufficiently old brown dwarfs will be too faint to be detectable.

Clouds are used to explain the weakening of the iron hydride (FeH) in late L-dwarfs. Iron clouds deplete FeH in the upper atmosphere and the cloud layer blocks the view to lower layers still containing FeH. The later strengthening of this chemical compound at cooler temperatures of mid- to late T-dwarfs is explained by disturbed clouds that allows a telescope to look into the deeper layers of the atmosphere that still contains FeH.[28] Young L/T-dwarfs (L2-T4) show high variability, which could be explained with clouds, hot spots, magnetically driven aurorae or thermochemical instabilities.[29] The clouds of these brown dwarfs are explained as either iron clouds with varying thickness or a lower thick iron cloud layer and an upper silicate cloud layer. This upper silicate cloud layer can consist out of quartz, enstatite, corundum and/or fosterite.[30][31] It is however not clear if silicate clouds are



Cloud models for the early T-type brown dwarfs SIMP J0136+09 and 2MASS J2139+02 (left two panels) and the late T-type brown dwarf 2M0050–3322.

always necessary for young objects.[32] Silicate absorption can be directly observed in the mid-infrared at 8 to 12 μm. Observations with Spitzer IRS has shown that silicate absorption is common, but not ubiquitous, for L2-L8 dwarfs.[33] Additionally MIRI observed silicate absorption in the planetary-mass companion VHS 1256b.[34]

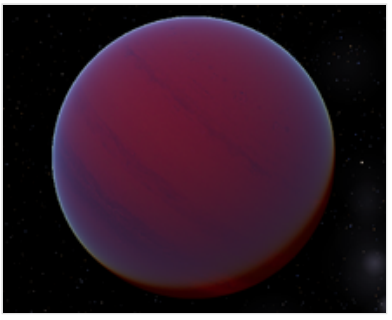
Iron rain as part of atmospheric convection processes is possible only in brown dwarfs, and not in small stars. The spectroscopy research into iron rain is still ongoing, but not all brown dwarfs will always have this atmospheric anomaly. In 2013, a heterogeneous iron-containing atmosphere was imaged around the B component in the nearby Luhman 16 system.[35]

For late T-type brown dwarfs only a few variable searches were carried out. Thin cloud layers are predicted to form in late T-dwarfs from chromium and potassium chloride, as well as several sulfides. These sulfides are manganese sulfide, sodium sulfide and zink sulfide.[36] The variable T7 dwarf 2M0050–3322 is explained to have a top layer of potassium chloride clouds, a mid layer of sodium sulfide clouds and a lower layer of manganese sulfide clouds. Patchy clouds of the top two cloud layers could explain why the methane and water vapor bands are variable.[37]

At the lowest temperatures of the Y-dwarf WISE 0855-0714 patchy cloud layers of sulfide and water ice clouds could cover 50% of the surface.[38]

Low-mass brown dwarfs versus high-mass planets

Like stars, brown dwarfs form independently, but, unlike stars, they lack sufficient mass to "ignite" hydrogen fusion. Like all stars, they can occur singly or in close proximity to other stars. Some orbit stars and can, like planets, have eccentric orbits.



An artistic concept of the brown dwarf around the star HD 29587, a companion known as HD 29587 b, and estimated to be about 55 Jupiter masses

Size and fuel-burning ambiguities

Brown dwarfs are all roughly the same radius as Jupiter. At the high end of their mass range (60–90 M_J), the volume of a brown dwarf is governed primarily by electron-degeneracy pressure,[39] as it is in white dwarfs; at the low end of the range (10 M_J), their volume is governed primarily by Coulomb pressure, as it is in planets. The net result is that the radii of brown dwarfs vary by only 10–15% over the range of possible masses. Moreover, the mass–radius relationship shows no change from about one Saturn mass to the onset of hydrogen burning ($0.080 \pm 0.008\ M_\odot$), suggesting that from this perspective brown dwarfs are simply high-mass Jovian planets.[40] This can make distinguishing them from planets difficult.

In addition, many brown dwarfs undergo no fusion; even those at the high end of the mass range (over 60 M_J) cool quickly enough that after 10 million years they no longer undergo fusion.

Heat spectrum

X-ray and infrared spectra are telltale signs of brown dwarfs. Some emit X-rays; and all "warm" dwarfs continue to glow tellingly in the red and infrared spectra until they cool to planet-like temperatures (under 1,000 K).

Gas giants have some of the characteristics of brown dwarfs. Like the Sun, Jupiter and Saturn are both made primarily of hydrogen and helium. Saturn is nearly as large as Jupiter, despite having only 30% the mass. Three of the giant planets in the Solar System (Jupiter, Saturn, and Neptune) emit much more (up to about twice) heat than they receive from the Sun.[41][42] All four giant planets have their own "planetary" systems, in the form of extensive moon systems.

Current IAU standard

Currently, the International Astronomical Union considers an object above 13 M_J (the limiting mass for thermonuclear fusion of deuterium) to be a brown dwarf, whereas an object under that mass (and orbiting a star or stellar remnant) is considered a planet. The minimum mass required to trigger sustained hydrogen burning (about 80 M_J) forms the upper limit of the definition.[3][43]

It is also debated whether brown dwarfs would be better defined by their formation process rather than by theoretical mass limits based on nuclear fusion reactions.[4] Under this interpretation brown dwarfs are those objects that represent the lowest-mass products of the star formation process, while planets are objects formed in an accretion disk surrounding a star. The coolest free-floating objects discovered such as WISE 0855, as well as the lowest-mass young objects known like PSO J318.5−22, are thought to have masses below 13 M_J, and as a result are sometimes referred to as planetary mass objects due to the ambiguity of whether they should be regarded as rogue planets or brown dwarfs. There are planetary mass objects known to orbit brown dwarfs, such as 2M1207b, MOA-2007-BLG-192Lb, 2MASS J044144b and Oph 98 B.

The 13 Jupiter-mass cutoff is a rule of thumb rather than something of precise physical significance. Larger objects will burn most of their deuterium and smaller ones will burn only a little, and the 13 Jupiter-mass value is somewhere in between.[44] The amount of deuterium burnt also depends to some extent on the composition of the object, specifically on the amount of helium and deuterium present and on the fraction of heavier elements, which determines the atmospheric opacity and thus the radiative cooling rate.[45]

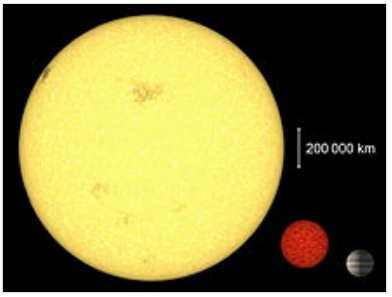
As of 2011 the Extrasolar Planets Encyclopaedia included objects up to 25 Jupiter masses, saying, "The fact that there is no special feature around 13 M_{Jup} in the observed mass spectrum reinforces the choice to forget this mass limit".[46] As of 2016, this limit was increased to 60 Jupiter masses,[47] based on a study of mass–density relationships.[48]

The Exoplanet Data Explorer includes objects up to 24 Jupiter masses with the advisory: "The 13 Jupiter-mass distinction by the IAU Working Group is physically unmotivated for planets with rocky cores, and observationally problematic due to the sin i ambiguity."[49] The NASA Exoplanet Archive includes objects with a mass (or minimum mass) equal to or less than 30 Jupiter masses.[50]

Sub-brown dwarf

Objects below 13 M_J, called **sub-brown dwarf** or **planetary-mass brown dwarf**, form in the same manner as stars and brown dwarfs (i.e. through the collapse of a gas cloud) but have a mass below the limiting mass for thermonuclear fusion of deuterium.[51]

Some researchers call them free-floating planets,[52] whereas others call them planetary-mass brown dwarfs.[53]



A size comparison between the Sun, a young sub-brown dwarf, and Jupiter. As the sub-brown dwarf ages, it will gradually cool and shrink.

Role of other physical properties in the mass estimate

While spectroscopic features can help to distinguish between low mass stars and brown dwarfs, it is often necessary to estimate the mass to come to a conclusion. The theory behind the mass estimate is that brown dwarfs with a similar mass form in a similar way and are hot when they form. Some have spectral types that are similar to low-mass stars, such as 2M1101AB. As they cool down the brown dwarfs should retain a range of luminosities depending on the mass.[54] Without the age and luminosity a mass estimate is difficult; for example, an L-type brown dwarf could be an old brown dwarf with a high mass (possibly a low-mass star) or a young brown dwarf with a very low mass. For Y dwarfs this is less of a problem as they remain low-mass objects near the sub-brown dwarf limit, even for relative high age estimates.[55] For L and T dwarfs it is still useful to have an accurate age estimate. The luminosity is here the less concerning property, as this can be estimated from the spectral energy distribution.[56] The age estimate can be done in two ways. Either the brown dwarf is young and still has spectral features that are associated with youth or the brown dwarf co-moves with a star or stellar group (star cluster or association), which have easier to obtain age estimates. A very young brown dwarf that was further studied with this method is 2M1207 and the companion 2M1207b. Based on the location, proper motion and spectral signature, this object was determined to belong to the ~8 million year old TW Hydrae association and the mass of the secondary was determined to be below the deuterium burning limit with 8 ± 2 M_J.[57] A very old example of an age estimate that makes use of co-movement is the brown dwarf + white dwarf binary COCONUTS-1, with the white dwarf

having a total age of $7.3\ ^{+2.8}_{-1.6}$ billion years. In this case the mass was not estimated with the derived age, but the co-movement provided an accurate distance estimate, using Gaia parallax. Using this measurement the authors estimated the radius, which was then used to estimate the mass for the brown dwarf as $15.4\ ^{+0.9}_{-0.8}\ M_J$.[58]

Observations

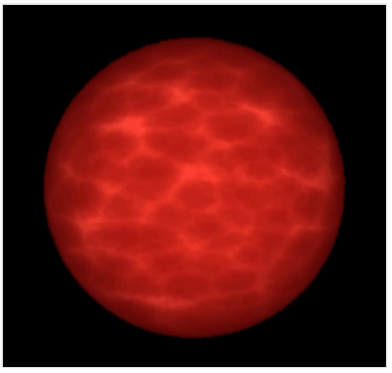
Classification of brown dwarfs

Spectral class M

Artist's vision of a late-M dwarf

These are brown dwarfs with a spectral class of M5.5 or later; they are also called late-M dwarfs. These can be considered red dwarfs in the eyes of some scientists. Many brown dwarfs with spectral type M are young objects, such as Teide 1.

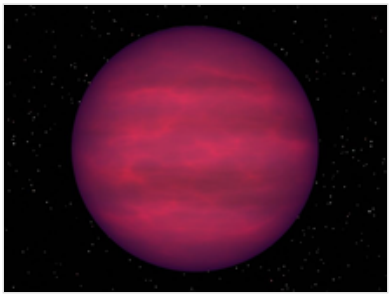
Spectral class L



Artist's concept of an L dwarf

The defining characteristic of spectral class M, the coolest type in the long-standing classical stellar sequence, is an optical spectrum dominated by absorption bands of titanium(II) oxide (TiO) and vanadium(II) oxide (VO) molecules. However, GD 165B, the cool companion to the white dwarf GD 165, had none of the hallmark TiO features of M dwarfs. The subsequent identification of many objects like GD 165B ultimately led to the definition of a new spectral class, the **L dwarfs**, defined in the red optical region of the spectrum not by metal-oxide absorption bands (TiO, VO), but by metal hydride emission bands (FeH, CrH, MgH, CaH) and prominent atomic lines of alkali metals (Na, K, Rb, Cs). As of 2013, over 900 L dwarfs have been identified,[23] most by wide-field surveys: the Two Micron All Sky Survey (2MASS), the Deep Near Infrared Survey of the Southern Sky (DENIS), and the Sloan Digital Sky Survey (SDSS). This spectral class contains not only the brown dwarfs, because the coolest main-sequence stars above brown dwarfs (> 80 M_J) have the spectral class L2 to L6.[59]

Spectral class T

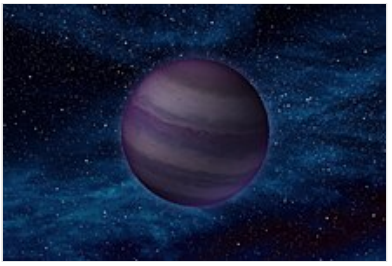


Artist's concept of a T dwarf

As GD 165B is the prototype of the L dwarfs, Gliese 229B is the prototype of a second new spectral class, the **T dwarfs**. T dwarfs are pinkish-magenta. Whereas near-infrared (NIR) spectra of L dwarfs show strong absorption bands of H_2O and carbon monoxide (CO), the NIR spectrum of Gliese 229B is dominated by absorption bands from methane (CH_4), features that were found only in the giant planets of the Solar System and Titan. CH_4, H_2O, and molecular hydrogen (H_2) collision-induced absorption (CIA) give Gliese 229B blue near-infrared colors. Its steeply sloped red optical spectrum also lacks the FeH and CrH bands that characterize L dwarfs and instead is influenced by exceptionally broad absorption features from the alkali metals Na and K. These differences led J. Davy Kirkpatrick to propose the T spectral class for objects exhibiting H- and K-band CH_4 absorption. As of 2013, 355 T dwarfs are known.[23] NIR classification schemes for T dwarfs have recently been developed by Adam Burgasser and Tom Geballe. Theory suggests that L dwarfs are a mixture of very-low-mass stars and sub-stellar objects (brown dwarfs), whereas the T dwarf class is composed entirely of brown dwarfs. Because of the absorption of sodium and potassium in the green part of the spectrum of T dwarfs, the actual appearance of T dwarfs to human visual perception is estimated to be not brown, but magenta.[60][61] T-class brown dwarfs, such as WISE 0316+4307, have been detected more than 100 light-years from the Sun.

Spectral class Y

In 2009, the coolest-known brown dwarfs had estimated effective temperatures between 500 and 600 K (227–327 °C; 440–620 °F), and have been assigned the spectral class T9. Three examples are the brown dwarfs CFBDS J005910.90–011401.3, ULAS J133553.45+113005.2 and ULAS J003402.77−005206.7.[62] The spectra of these objects have absorption peaks around 1.55 micrometres.[62] Delorme et al. have suggested that this feature is due to absorption from ammonia and that this should be taken as indicating the T–Y transition, making these objects of type Y0.[62][63] However, the feature is difficult to distinguish from absorption by water and methane,[62] and other authors have stated that the assignment of class Y0 is premature.[64]


Artist's vision of a Y dwarf

The first JWST spectral energy distribution of a Y-dwarf was able to observe several bands of molecules in the atmosphere of the Y0-dwarf WISE 0359−5401. The observations covered spectroscopy from 1 to 12 μm and photometry at 15, 18 and 21 μm. The molecules water (H_2O), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2) and ammonia (NH_3) were detected in WISE 0359−5401. Many of these features have been observed before in this Y-dwarf and warmer T-dwarfs by other observatories, but JWST was able to observe them in a single spectrum. Methane is the main reservoir of carbon in the atmosphere of WISE 0359−5401, but there is still enough carbon left to form detectable carbon monoxide (at 4.5–5.0 μm) and carbon dioxide (at 4.2–4.35 μm) in the Y-dwarf. Ammonia has been difficult to detect before JWST, as it blends in with the absorption feature of water in the near-infrared, as well at 5.5–7.1 μm. At longer wavelengths of 8.5–12 μm the spectrum of WISE 0359−5401 is dominated by the absorption of ammonia. At 3 μm there is an additional newly detected ammonia feature.[65]

Colder lower atmosphere

Usually brown dwarfs have a pressure-temperature (P-T) profile in an adiabatic form, which means that the pressure and temperature increases with depth. JWST spectroscopy and photometry suggests that Y-dwarfs have P-T profile that is not in the standard adiabatic form. This means that upper layers of the atmosphere have a warmer temperature and lower layers of the atmosphere have a colder temperature. This is explained with the rapid rotation of these isolated objects. The rapid rotation leads to dynamical, thermal, and chemical changes, which disrupts the convective transport of heat from the lower to the upper atmosphere. This different P-T profile influences the shape of the spectrum and influences the composition of carbon and nitrogen bearing molecules in the atmosphere of Y-dwarfs.[66]

Individual Y-dwarf discoveries

In April 2010, two newly discovered ultracool sub-brown dwarfs (UGPS 0722-05 and SDWFS 1433+35) were proposed as prototypes for spectral class Y0.[67]

In February 2011, Luhman et al. reported the discovery of WD 0806−661 B, a brown dwarf companion to a nearby white dwarf with a temperature of c. 300 K (27 °C; 80 °F) and mass of 7 M_J.[68] Though of planetary mass, Rodriguez et al. suggest it is unlikely to have formed in the same manner as planets.[69]

Shortly after that, Liu et al. published an account of a "very cold" (c. 370 K (97 °C; 206 °F)) brown dwarf orbiting another very-low-mass brown dwarf and noted that "Given its low luminosity, atypical colors and cold temperature, CFBDS J1458+10B is a promising candidate for the hypothesized Y spectral class."[70]

In August 2011, scientists using data from NASA's Wide-field Infrared Survey Explorer (WISE) discovered six objects that they classified as Y dwarfs with temperatures as cool as 25 °C (298 K; 77 °F).[71][72]

WISE data has revealed hundreds of new brown dwarfs. Of these, fourteen are classified as cool Ys.[23] One of the Y dwarfs, called WISE 1828+2650, was, as of August 2011, the record holder for the coldest brown dwarf—emitting no visible light at all, this type of object resembles free-floating planets more than stars. WISE 1828+2650 was initially estimated to have an atmospheric temperature cooler than 300 K (27 °C; 80 °F).[73] Its temperature has since been revised and newer estimates put it in the range of 250 to 400 K (−23 to 127 °C; −10 to 260 °F).[74]

In April 2014, WISE 0855−0714 was announced with a temperature profile estimated around 225 to 260 K (−48 – −13 °C; −55–8 °F) and a mass of 3 to 10 M_J.[75] It was also unusual in that its observed parallax meant a distance close to 7.2 ± 0.7 light-years from the Solar System.

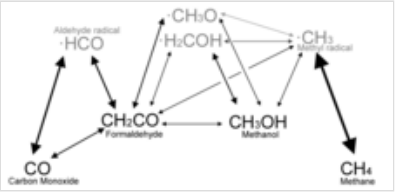
The CatWISE catalog combines NASA's WISE and NEOWISE survey.[76] It expands the number of faint sources and is therefore used to find the faintest brown dwarfs, including Y dwarfs. Seventeen candidate Y dwarfs were discovered by the CatWISE researchers. Initial color with the Spitzer Space Telescope indicated that CW1446 is one of the reddest and coldest Y dwarfs.[77] Additional data with Spitzer showed that CW1446 is the fifth reddest brown dwarf with a temperature of about 310 to 360 K (37–87 °C; 98–188 °F) at a distance of about 10 parsec.[55]

A search of the CatWISE catalog in 2019 revealed CWISEP J1935-1546, one of the coldest brown dwarfs with an estimated temperature of 270 to 360 K (−3–87 °C; 26–188 °F).[78] In 2023 it was announced that CWISEP J1935-1546 has methane emission due to an aurora.[79]

In January 2020 the discovery of WISE J0830+2837, initially discovered by citizen scientists of the Backyard Worlds project, was presented at the 235th meeting of the American Astronomical Society. This Y dwarf is 36.5 light-years distant from the Solar System and has a temperature of about 350 K (77 °C; 170 °F).[80]

WISE 0458+6434 is the first ultra-cool brown dwarf (green dot) discovered by WISE. The green and blue comes from infrared wavelengths mapped to visible colors.

Role of vertical mixing



Major chemical pathways linking carbon monoxide and methane.The short-lived radicals are marked with a dot. Adopted from Zahnle & Marley[81]

In the hydrogen-dominated atmosphere of brown dwarfs a chemical equilibrium between carbon monoxide and methane exists. Carbon monoxide reacts with hydrogen molecules and forms methane and hydroxy in this reaction. The hydroxy radical might later react with hydrogen and form water molecules. In the other direction of the reaction methane reacts with hydroxy and forms carbon monoxide and hydrogen. The chemical reaction is tilted towards carbon monoxide at higher temperatures (L-dwarfs) and lower pressure. At lower temperatures (T-dwarfs) and higher pressure the reaction is tilted towards methane and methane predominates at the T/Y-boundary. Vertical mixing of the atmosphere can however cause methane to sink into lower layers of the atmosphere and carbon monoxide to rise from these lower and hotter layers. The carbon monoxide is slow to react back into methane because of an energy barrier that prevents the breakdown of the C-O bonds. This forces the observable atmosphere of a brown dwarf to be in a chemical disequilibrium. The L/T transition is mainly defined with the transition from a carbon monoxide dominated atmosphere in L-dwarfs to a methane dominated atmosphere in T-dwarfs. The amount of vertical mixing can therefore push the L/T-transition to lower or higher temperatures. This becomes important for objects with modest surface gravity and extended atmospheres, such as giant exoplanets. This pushes the L/T transition to lower temperatures for giant exoplanets. For brown dwarfs this transition occurs at around 1200 K. The exoplanet HR 8799c on the other hand does not show any methane, while having a temperature of 1100K.[81]

The transition between T/Y-dwarfs is often defined at around 500 K due to missing spectral observations of these cold and faint objects.[82] Future observations with JWST and the ELTs might improve the sample of Y-dwarfs with observed spectra. Y-dwarfs are dominated by deep spectral features of methane, water vapor and possibly absorption features of ammonia and water ice.[82] Vertical mixing, clouds, metallicity, photochemistry, lightning, impact shocks and metallic catalysts might influence the temperature at which the L/T and T/Y transition occurs.[81]

Secondary features

Young brown dwarfs have low surface gravities because they have larger radii and lower masses compared to the field stars of similar spectral type. These sources are marked by a letter beta (β) for intermediate surface gravity and gamma (γ) for low surface gravity. Indication for low surface gravity are weak CaH, K I and Na I lines, as well as strong VO line.[85] Alpha (α) stands for normal surface gravity and is usually dropped. Sometimes an extremely low surface gravity is denoted by a delta (δ).[87] The suffix "pec" stands for peculiar. The peculiar suffix is still used for other features that are unusual and summarizes different properties, indicative of low surface gravity, subdwarfs and unresolved binaries.[88] The prefix sd stands for subdwarf and only includes cool subdwarfs. This prefix indicates a low metallicity and kinematic properties that are more similar to halo stars than to disk stars.[84] Subdwarfs appear bluer than disk objects.[89] The red suffix describes objects with red color, but an older age. This is not interpreted as low surface gravity, but as a high dust content.[86][87] The

blue suffix describes objects with blue near-infrared colors that cannot be explained with low metallicity. Some are explained as L+T binaries, others are not binaries, such as 2MASS J11263991−5003550 and are explained with thin and/or large-grained clouds.[87]

Brown dwarf spectral types

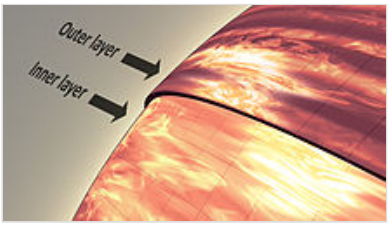
Secondary features	
pec	This suffix (e.g. L2pec) stands for "peculiar".[83]
sd	This prefix (e.g. sdL0) stands for subdwarf and indicates a low metallicity and blue color[84]
β	Objects with the beta (β) suffix (e.g. L4β) have an intermediate surface gravity.[85]
γ	Objects with the gamma (γ) suffix (e.g. L5γ) have a low surface gravity.[85]
red	The red suffix (e.g. L0red) indicates objects without signs of youth, but high dust content[86]
blue	The blue suffix (e.g. L3blue) indicates unusual blue near-infrared colors for L dwarfs without obvious low metallicity[87]

Spectral and atmospheric properties of brown dwarfs

The majority of flux emitted by L and T dwarfs is in the 1- to 2.5-micrometre near-infrared range. Low and decreasing temperatures through the late-M, -L, and -T dwarf sequence result in a rich near-infrared spectrum containing a wide variety of features, from relatively narrow lines of neutral atomic species to broad molecular bands, all of which have different dependencies on temperature, gravity, and metallicity. Furthermore, these low temperature conditions favor condensation out of the gas state and the formation of grains.

Wind measured (Spitzer ST; Artist Concept; 9 Apr 2020)[90]

Typical atmospheres of known brown dwarfs range in temperature from 2,200 down to 750 K.[60] Compared to stars, which warm themselves with steady internal fusion, brown dwarfs cool quickly over time; more massive dwarfs cool more slowly than less massive ones. There is some evidence that the cooling of brown dwarfs slows down at the transition between spectral classes L and T (about 1000 K).[91]



Artist's illustration of a brown dwarf's interior structure. Cloud layers at certain depths are offset as a result of layer shifting.

Observations of known brown dwarf candidates have revealed a pattern of brightening and dimming of infrared emissions that suggests relatively cool, opaque cloud patterns obscuring a hot interior that is stirred by extreme winds. The weather on such bodies is thought to be extremely strong, comparable to but far exceeding Jupiter's famous storms.

On January 8, 2013, astronomers using NASA's Hubble and Spitzer space telescopes probed the stormy atmosphere of a brown dwarf named 2MASS J22282889–4310262, creating the most detailed "weather map" of a brown dwarf thus far. It shows wind-driven, planet-sized clouds. The new research is a stepping stone toward a better understanding not only brown dwarfs, but also of the atmospheres of planets beyond the Solar System.[92]

In April 2020 scientists reported clocking wind speeds of +650 ± 310 metres per second (up to 1,450 miles per hour) on the nearby brown dwarf 2MASS J10475385+2124234. To calculate the measurements, scientists compared the rotational movement of atmospheric features, as ascertained by brightness changes, against the electromagnetic rotation generated by the brown dwarf's interior. The results confirmed previous predictions that brown dwarfs would have high winds. Scientists are hopeful that this comparison method can be used to explore the atmospheric dynamics of other brown dwarfs and extrasolar planets.[93]

Observational techniques

Coronagraphs have recently been used to detect faint objects orbiting bright visible stars, including Gliese 229B.

Sensitive telescopes equipped with charge-coupled devices (CCDs) have been used to search distant star clusters for faint objects, including Teide 1.

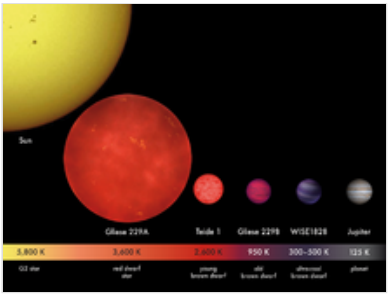
Wide-field searches have identified individual faint objects, such as Kelu-1 (30 light-years away).

Brown dwarfs are often discovered in surveys to discover exoplanets. Methods of detecting exoplanets work for brown dwarfs as well, although brown dwarfs are much easier to detect.

Brown dwarfs can be powerful emitters of radio emission due to their strong magnetic fields. Observing programs at the Arecibo Observatory and the Very Large Array have detected over a dozen such objects, which are also called ultracool dwarfs because they share common magnetic properties with other objects in this class.[94] The detection of radio emission

from brown dwarfs permits their magnetic field strengths to be measured directly.

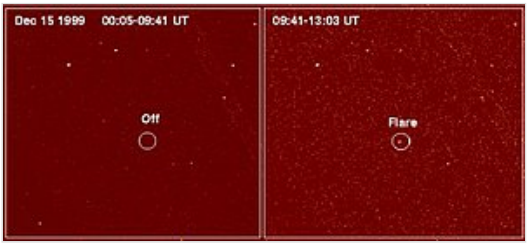
Milestones



Brown dwarfs Teide 1, Gliese 229B, and WISE 1828+2650 compared to red dwarf Gliese 229A, Jupiter and our Sun

- 1995: First brown dwarf verified. Teide 1, an M8 object in the Pleiades cluster, is picked out with a CCD in the Spanish Observatory of Roque de los Muchachos of the Instituto de Astrofísica de Canarias.
- First methane brown dwarf verified. Gliese 229B is discovered orbiting red dwarf Gliese 229A (20 ly away) using an adaptive optics coronagraph to sharpen images from the 60-inch (1.5 m) reflecting telescope at Palomar Observatory on Southern California's Mt. Palomar; follow-up infrared spectroscopy made with their 200-inch (5.1 m) Hale telescope shows an abundance of methane.
- 1998: First X-ray-emitting brown dwarf found. Cha Helpha 1, an M8 object in the Chamaeleon I dark cloud, is determined to be an X-ray source, similar to convective late-type stars.
- 15 December 1999: First X-ray flare detected from a brown dwarf. A team at the University of California monitoring LP 944-20 (60 M_J, 16 ly away) via the Chandra X-ray Observatory, catches a 2-hour flare.[95]
- 27 July 2000: First radio emission (in flare and quiescence) detected from a brown dwarf. A team of students at the Very Large Array detected emission from LP 944–20.[96]
- 30 April 2004: First detection of a candidate exoplanet around a brown dwarf: 2M1207b discovered with the VLT and the first directly imaged exoplanet.[97]
- 20 March 2013: Discovery of the closest brown dwarf system: Luhman 16.[98]
- 25 April 2014: Coldest-known brown dwarf discovered. WISE 0855−0714 is 7.2 light-years away (seventh-closest system to the Sun) and has a temperature between −48 and −13 °C.[75]

Brown dwarf as an X-ray source



Chandra image of LP 944-20 before flare and during flare

X-ray flares detected from brown dwarfs since 1999 suggest changing magnetic fields within them, similar to those in very-low-mass stars.

With no strong central nuclear energy source, the interior of a brown dwarf is in a rapid boiling, or convective state. When combined with the rapid rotation that most brown dwarfs exhibit, convection sets up conditions for the development of a strong, tangled magnetic field near the surface. The flare observed by Chandra from LP 944-20 could have its origin in the turbulent magnetized hot material beneath the brown dwarf's surface. A sub-surface flare could conduct heat to the atmosphere, allowing electric currents to flow and produce an X-ray flare, like a stroke of lightning. The absence of X-rays from LP 944-20 during the non-flaring period is also a significant result. It sets the lowest observational limit on steady X-ray power produced by a brown dwarf, and shows that coronas cease to exist as the surface temperature of a brown dwarf cools below about 2,800 K and becomes electrically neutral.

Using NASA's Chandra X-ray Observatory, scientists have detected X-rays from a low-mass brown dwarf in a multiple star system.[99] This is the first time that a brown dwarf this close to its parent star(s) (Sun-like stars TWA 5A) has been resolved in X-rays.[99] "Our Chandra data show that the X-rays originate from the brown dwarf's coronal plasma which is some 3 million degrees Celsius", said Yohko Tsuboi of Chuo University in Tokyo.[99] "This brown dwarf is as bright as the Sun today in X-ray light, while it is fifty times less massive than the Sun", said Tsuboi.[99] "This observation, thus, raises the possibility that even massive planets might emit X-rays by themselves during their youth!"[99]

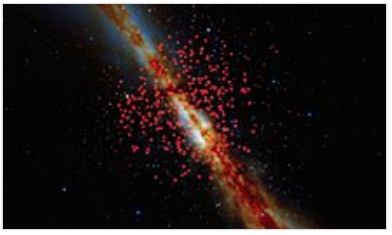
Brown dwarfs as radio sources

The first brown dwarf that was discovered to emit radio signals was LP 944-20, which was observed based on its X-ray emission. Approximately 5–10% of brown dwarfs appear to have strong magnetic fields and emit radio waves, and there may be as many as 40 magnetic brown dwarfs within 25 pc of the Sun based on Monte Carlo modeling and their average spatial density.[100] The power of the radio emissions of brown dwarfs is roughly constant despite variations in their

temperatures.[94] Brown dwarfs may maintain magnetic fields of up to 6 kG in strength.[101] Astronomers have estimated brown dwarf magnetospheres to span an altitude of approximately 10^7 m given properties of their radio emissions.[102] It is unknown whether the radio emissions from brown dwarfs more closely resemble those from planets or stars. Some brown dwarfs emit regular radio pulses, which are sometimes interpreted as radio emission beamed from the poles, but may also be beamed from active regions. The regular, periodic reversal of radio wave orientation may indicate that brown dwarf magnetic fields periodically reverse polarity. These reversals may be the result of a brown dwarf magnetic activity cycle, similar to the solar cycle.[103]

Recent developments

Estimates of brown dwarf populations in the solar neighbourhood suggest that there may be as many as six stars for every brown dwarf.[105] A more recent estimate from 2017 using the young massive star cluster RCW 38 concluded that the Milky Way galaxy contains between 25 and 100 billion brown dwarfs.[106] (Compare these numbers to the estimates of the number of stars in the Milky Way; 100 to 400 billion.)



A visualization representing a three-dimensional map of brown dwarfs (red dots) that have been discovered within 65 light-years of the Sun[104]

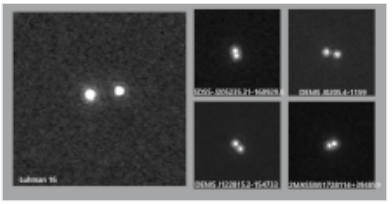
In a study published in Aug 2017 NASA's Spitzer Space Telescope monitored infrared brightness variations in brown dwarfs caused by cloud cover of variable thickness. The observations revealed large-scale waves propagating in the atmospheres of brown dwarfs (similarly to the atmosphere of Neptune and other Solar System giant planets). These atmospheric waves modulate the thickness of the clouds and propagate with different velocities (probably due to differential rotation).[107]

In August 2020, astronomers discovered 95 brown dwarfs near the Sun through the project Backyard Worlds: Planet 9.[108]

Binary brown dwarfs

Brown dwarf-Brown dwarf binaries

Brown dwarfs binaries of type M, L, and T are less common with a lower mass of the primary.[109] L-dwarfs have a binary fraction of about 24^{+6}_{-2}% and the binary fraction for late T, early Y-dwarfs (T5-Y0) is about 8±6%.[110]



Multi-epoch images of brown dwarf binaries taken with the Hubble Space Telescope. The binary Luhman 16 AB (left) is closer to the Solar System than the other examples shown here.

Brown dwarf binaries have a higher companion-to-host ratio $q = M_B/M_A$ for lower mass binaries. Binaries with a M-type star as a primary have for example a broad distribution of q with a preference of q≥0.4. Brown dwarfs on the other hand show a strong preference for q≥0.7. The separation is decreasing with mass: M-type stars have a separation peaking at 3-30 astronomical units (au), M-L-type brown dwarfs have a projected separation peaking at 5-8 au and T5-Y0 objects have a projected separation that follows a lognormal distribution with a peak separation of about 2.9 au.[110]

An example is the closest brown dwarf binary Luhman 16 AB with a primary L7.5 dwarf and a separation of 3.5 au and q=0.85. The separation is on the lower end of the expected separation for M-L-type brown dwarfs, but the mass ratio is typical.

It is not known if the same trend continues with Y-dwarfs, because their sample size is so small. The Y+Y dwarf binaries should have a high mass ratio q and a low separation, reaching scales of less than one au.[111] The Y+Y dwarf WISE J0336-0143 was recently confirmed as a binary with JWST and it has a mass ratio of q=0.62±0.05 and a separation of 0.97 astronomical units. The researchers point out that the sample size of low-mass binary brown dwarfs is too small to determine if WISE J0336-0143 is a typical representative of low-mass binaries or a peculiar system.[112]

Observations of the orbit of binary systems containing brown dwarfs can be used to measure the mass of the brown dwarf. In the case of 2MASSW J0746425+2000321, the secondary weighs 6% of the solar mass. This measurement is called a dynamical mass.[113][114] The brown dwarf system closest to the Solar System is the binary Luhman 16. It was attempted to

search for planets around this system with a similar method, but none were found.[115]

Unusual brown dwarf binaries

The wide brown dwarf binary SDSS J1416+1348

The wide binary system 2M1101AB was the first binary with a separation greater than 20 AU. The discovery of the system gave definitive insights to the formation of brown dwarfs. It was previously thought that wide binary brown dwarfs are not formed or at least are disrupted at ages of 1–10 Myr. The existence of this system is also inconsistent with the ejection hypothesis.[116] The ejection hypothesis was a proposed hypothesis in which brown dwarfs form in a multiple system, but are ejected before they gain enough mass to burn hydrogen.[117]

More recently the wide binary W2150AB was discovered. It has a similar mass ratio and binding energy as 2M1101AB, but a greater age and is located in a different region of the galaxy. While 2M1101AB is in a closely crowded region, the binary W2150AB is in a sparsely-separated field. It must have survived any dynamical interactions in its natal star cluster. The binary belongs also to a few L+T binaries that can be easily resolved by ground-based observatories. The other two are SDSS J1416+13AB and Luhman 16.[118]

There are other interesting binary systems such as the eclipsing binary brown dwarf system 2MASS J05352184–0546085.[119] Photometric studies of this system have revealed that the less massive brown dwarf in the system is hotter than its higher-mass companion.[120]

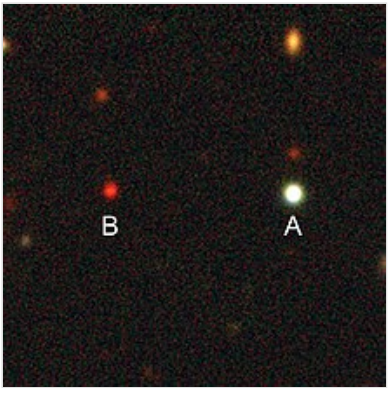
Brown dwarfs around stars

Brown dwarfs and massive planets in a close orbit (less than 5 au) around stars are rare and this is sometimes described as the brown dwarf desert. Less than 1% of stars with the mass of the sun have a brown dwarf within 3-5 au.[121]

An example for a star-brown dwarf binary is the first discovered T-dwarf Gliese 229 B, which orbits around the main-sequence star Gliese 229 A, a red dwarf. Brown dwarfs orbiting subgiants are also known, such as TOI-1994b which orbits its star every 4.03 days.[122]

There is also disagreement if some low-mass brown dwarfs should be considered planets. The NASA Exoplanet archive includes brown dwarfs with a minimum mass less or equal to 30 Jupiter masses as planets as long as there are other criteria fulfilled (e.g. orbiting a star).[123] The Working Group on Extrasolar Planets (WGESP) of the IAU on the other hand only considers planets with a mass below 13 Jupiter masses.[124]

White dwarf-Brown dwarf binaries



LSPM J0241+2553AB, a wide white dwarf(A)-brown dwarf(B) binary.

Brown dwarfs around white dwarfs are quite rare. GD 165 B, the prototype of the L dwarfs, is one such system.[125] Such systems can be useful in determining the age of the system and the mass of the brown dwarf. Other white dwarf-brown dwarf binaries are COCONUTS-1 AB (7 billion years old),[58] and LSPM J0055+5948 AB (10 billion years old),[126] SDSS J22255+0016 AB (2 billion years old)[127] WD 0806−661 AB (1.5-2.7 billion years old).[128]

Systems with close, tidally locked brown dwarfs orbiting around white dwarfs belong to the post common envelope binaries or PCEBs. Only 8 confirmed PCEBs containing a white dwarf with a brown dwarf companion are known, including WD 0137-349 AB. In the past history of these close white dwarf-brown dwarf binaries, the brown dwarf is engulfed by the star in the red giant phase. Brown dwarfs with a mass lower than 20 Jupiter masses would evaporate during the engulfment.[129][130] The dearth of brown dwarfs orbiting close to white dwarfs can be compared with similar observations of brown dwarfs around main-sequence stars, described as the brown-dwarf desert.[131][132] The PCEB might evolve into a cataclysmic variable star (CV*) with the brown dwarf as the donor.[133] Simulations have shown that highly evolved CV* are mostly associated with substellar donors (up to 80%).[134]

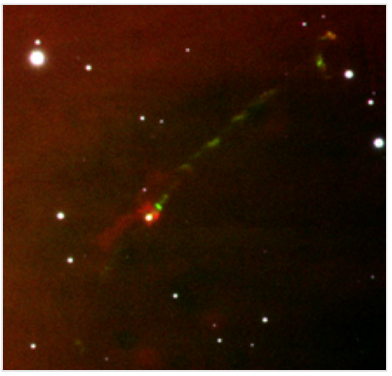
A type of CV*, called WZ Sge-type dwarf nova often show donors with a mass near the borderline of low-mass stars and brown dwarfs.[135] The binary BW Sculptoris is such a dwarf nova with a brown dwarf donor. This brown dwarf likely formed when a donor star lost enough mass to become a brown dwarf. The mass loss comes with a loss of the orbital period until it reaches a minimum of 70–80 minutes at which the period increases again. This gives this evolutionary stage the name period bouncer.[134] There could also exist brown dwarfs that merged with white dwarfs. The nova CK Vulpeculae might be a result of such a white dwarf–brown dwarf merger.[136][137]

Brown dwarfs around neutron stars

Substellar objects around neutron stars are known. An example are black widow pulsars, which are named after the original black widow pulsar PSR B1957+20. About 41 such black widows are known. A black widow pulsar is characterized by a millisecond pulsar with a substellar companion that is ablated by the strong stellar wind of the pulsar. If the companion has a mass below 0.1 $M_{\odot}$, it is called black widow, above this mass it is called redback pulsar.[138]

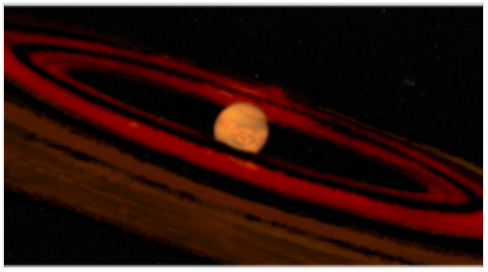
Formation and evolution

Brown dwarfs form similarly to stars and are surrounded by protoplanetary disks,[139] such as Cha 110913−773444. As of 2017 there is only one known proto-brown dwarf that is connected with a large Herbig–Haro object. This is the brown dwarf Mayrit 1701117, which is surrounded by a pseudo-disk and a Keplerian disk.[140] Mayrit 1701117 launches the 0.7-light-year-long jet HH 1165, mostly seen in ionized sulfur.[141][142]



The HH 1165 jet launched by the brown dwarf Mayrit 1701117 in the outer periphery of the sigma Orionis cluster

Disks around brown dwarfs have been found to have many of the same features as disks around stars; therefore, it is expected that there will be accretion-formed planets around brown dwarfs.[139] Given the small mass of brown dwarf disks, most planets will be terrestrial planets rather than gas giants.[143] If a giant planet orbits a brown dwarf across our line of sight, then, because they have approximately the same diameter, this would give a large signal for detection by transit.[144] The accretion zone for planets around a brown dwarf is very close to the brown dwarf itself, so tidal forces would have a strong effect.[143]



Artist's depiction of brown dwarf W1200-7845.

In 2020, the closest brown dwarf with an associated primordial disk—WISEA J120037.79-784508.3 (W1200-7845)—was discovered by the Disk Detective project when classification volunteers noted its infrared excess. It was vetted and analyzed by the science team who found that W1200-7845 had a 99.8% probability of being a member of the ε Chamaeleontis (ε Cha) young moving group association. Its parallax (using Gaia DR2 data) puts it at a distance of 102 parsecs (or 333 lightyears) from Earth—which is within the local Solar neighborhood.[145][146]

A paper from 2021 studied circumstellar discs around brown dwarfs in stellar associations that are a few million years old and 140 to 200 parsecs away. The researchers found that these disks are not massive enough to form planets in the future. There is evidence in these disks that might indicate that planet formation begins at earlier stages and that planets are already present in these disks. The evidence for disk evolution includes a decreasing disk mass over time, dust grain growth and dust settling.[147] Disks around brown dwarfs usually have a radius smaller than 40 astronomical units, but three disks in the more distant Taurus molecular cloud have a radius larger than 70 au and were resolved with ALMA. These larger disks are able to form rocky planets with a mass >1 M_{E}.[148] There are also brown dwarfs with disks in associations older than a few million years,[149] which might be evidence that disks around brown dwarfs need more time to dissipate. Especially old disks (>20 Myrs) are sometimes called Peter Pan disks. Currently 2MASS J02265658-5327032 is the only known brown dwarf that has a Peter Pan disk.[150]

The brown dwarf Cha 110913−773444, located 500 light-years away in the constellation Chamaeleon, may be in the process of forming a miniature planetary system. Astronomers from Pennsylvania State University have detected what they believe to be a disk of gas and dust similar to the one hypothesized to have formed the Solar System. Cha 110913−773444 is

the smallest brown dwarf found to date (8 M_J), and if it formed a planetary system, it would be the smallest-known object to have one.[151]

Planets around brown dwarfs

According to the IAU working definition (from August 2018) an exoplanet can orbit a brown dwarf. It requires a mass below 13 M_J and a mass ratio of $M/M_{central}<2/(25+\sqrt{621})$. This means that an object with a mass up to 3.2 M_J around a brown dwarf with a mass of 80 M_J is considered a planet. It also means that an object with a mass up to 0.52 M_J around a brown dwarf with a mass of 13 M_J is considered a planet.[153]

Artist's impression of a disc of dust and gas around a brown dwarf[152]

The super-Jupiter planetary-mass objects 2M1207b, 2MASS J044144 and Oph 98 B that are orbiting brown dwarfs at large orbital distances may have formed by cloud collapse rather than accretion and so may be sub-brown dwarfs rather than planets, which is inferred from relatively large masses and large orbits. The first discovery of a low-mass companion orbiting a brown dwarf (ChaHα8) at a small orbital distance using the radial velocity technique paved the way for the detection of planets around brown dwarfs on orbits of a few AU or smaller.[154][155] However, with a mass ratio between the companion and primary in ChaHα8 of about 0.3, this system rather resembles a binary star. Then, in 2008, the first planetary-mass companion in a relatively small orbit (MOA-2007-BLG-192Lb) was discovered orbiting a brown dwarf.[156]

Planets around brown dwarfs are likely to be carbon planets depleted of water.[157]

A 2017 study, based upon observations with Spitzer estimates that 175 brown dwarfs need to be monitored in order to guarantee (95%) at least one detection of a planet.[158]

Habitability

Habitability for hypothetical planets orbiting brown dwarfs has been studied. Computer models suggesting conditions for these bodies to have habitable planets are very stringent, the habitable zone being narrow, close (T dwarf 0.005 AU) and decreasing with time, due to the cooling of the brown dwarf (they fuse for at most 10 million years). The orbits there would have to be of extremely low eccentricity (on the order of 10 to the minus 6) to avoid strong tidal forces that would trigger a runaway greenhouse effect on the planets, rendering them uninhabitable. There would also be no moons.[159]

Superlative brown dwarfs

In 1984, it was postulated by some astronomers that the Sun may be orbited by an undetected brown dwarf (sometimes referred to as Nemesis) that could interact with the Oort cloud just as passing stars can. However, this hypothesis has fallen out of favor.[160]

Table of firsts

Record	Name	Spectral type	RA/Dec	Constellation	Notes
First discovered	Teide 1 (Pleiades Open Star Cluster)	M8	$3^h47^m18.0^s$ +24°22'31"	Taurus	Imaged in 1989 and 1994
First imaged with coronography	Gliese 229 B	T6.5	$06^h10^m34.62^s$ −21°51'52.1"	Lepus	Discovered 1994
First with planemo	2M1207	M8	$12^h07^m33.47^s$ −39°32'54.0"	Centaurus	Planet discovered in 2004
First with a circumstellar disk	ChaHα1	M7.5	$11^h07^m17.0^s$ -77°35'54"	Chamaeleon	Disk discovered in 2000, first disk around a bona fide brown dwarf, also first x-ray emitting[161]
First with bipolar outflow	Rho-Oph 102 (SIMBAD: [GY92] 102)		16 26 42.758 -24 41 22.24	Ophiuchus	partly resolved outflow[162]
First with large-scale Herbig-Haro object	Mayrit 1701117 (Herbig-Haro object: HH 1165)	proto-BD	05 40 25.799 -02 48 55.42	Orion	projected length of the Herbig-Haro object: 0.8 light-years (0.26 pc)[142]
First field type (solitary)	Teide 1	M8	$3^h47^m18.0^s$ +24°22'31"	Taurus	1995
First as a companion to a normal star	Gliese 229 B	T6.5	$06^h10^m34.62^s$ −21°51'52.1"	Lepus	1995
First spectroscopic binary brown dwarf	PPL 15 A, B[163]	M6.5	$03^h\ 48^m\ 4.659^s$ +23° 39′ 30.32″	Taurus	Basri and Martín 1999
First eclipsing binary brown dwarf	2M0535-05[164][120]	M6.5		Orion	Stassun 2006, 2007 (distance ~450 pc)
First binary brown dwarf of T Type	Epsilon Indi Ba, Bb[165]	T1 + T6	$22^h\ 03^m\ 21.65363^s$ −56° 47′ 09.5228″	Indus	Distance: 3.626pc
First binary brown dwarf of Y Type	WISE J0336−0143	Y+Y	$03^h\ 36^m\ 05.052^s$ −01° 43′ 50.48″	Eridanus	2023[112]
First trinary brown dwarf	DENIS-P J020529.0-115925 A/B/C	L5, L8 and T0	$02^h05^m29.40^s$ −11°59'29.7"	Cetus	Delfosse et al. 1997[166]
First halo brown dwarf	2MASS J05325346+8246465	sdL7	$05^h32^m53.46^s$ +82°46'46.5"	Gemini	Burgasser et al. 2003[167]
First with late-M spectrum	Teide 1	M8	$3^h47^m18.0^s$ +24°22'31"	Taurus	1995
First with L spectrum	GD 165B	L4	$14^h\ 24^m\ 39.144^s$ 09° 17′ 13.98″	Boötes	1988
First with T spectrum	Gliese 229 B	T6.5	$06^h10^m34.62^s$ −21°51'52.1"	Lepus	1995
Latest-T spectrum	ULAS J003402.77−005206.7	T9[64]		Cetus	2007
First with Y spectrum	CFBDS0059[63]	~Y0	$00^h\ 59^m\ 10.83^s$ −01° 14′ 01.3″	Cetus	2008; this is also classified as a T9 dwarf, due to its close resemblance to other T dwarfs.[64]

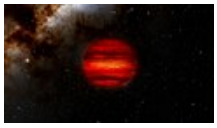
First X-ray-emitting	ChaHα1	M8		Chamaeleon	1998
First X-ray flare	LP 944–20	M9V	$03^h39^m35.22^s$ −35°25'44.1"	Fornax	1999
First radio emission (in flare and quiescence)	LP 944-20	M9V	$03^h39^m35.22^s$ −35°25'44.1"	Fornax	2000[96]
First potential brown dwarf auroras discovered	LSR J1835+3259	M8.5		Lyra	2015
First detection of differential rotation in a brown dwarf	TVLM 513-46546	M9	$15^h01^m08.3^s$ +22°50'02"	Boötes	Equator rotates faster than poles by 0.022 radians / day[168]
First confirmed brown dwarf to have survived the primary's red giant phase	WD 0137−349 B[169]	L8	$01^h\ 39^m\ 42.847^s$ −34° 42′ 39.32″	Sculptor (constellation)	

Table of extremes

Record	Name	Spectral type	RA/Dec	Constellation	Notes
Oldest	LSPM J0055+5948 B or Wolf 1130 C	T8	$00^h\ 55^m\ 58.300^s$ +59° 48′ 02.53″ or $20^h\ 05^m\ 02.1951^s$ +54° 26′ 03.234″	Cassiopeia or Cygnus	two of the few examples with a good age estimate: LSPM J0055B: 10±3 billion years[126][127] Wolf 1130C: >10 billion years[170]
Youngest	2MASS J05413280-0151272	M8.5	$05^h\ 41^m\ 32.801^s$ −01° 51′ 27.20″	Orion	One brown dwarf member of the about 0.5 Myr-old Flame Nebula. 20.9 M_J object[171]
Most massive	SDSS J010448.46+153501.8[172]	usdL1.5	$01^h04^m48.46^s$ +15°35'01.8"	Pisces	distance is ~180–290 pc, mass is ~88.5–91.7 M_J. Transitional brown dwarfs.
Metal-rich					
Metal-poor	SDSS J010448.46+153501.8[172]	usdL1.5	$01^h04^m48.46^s$ +15°35'01.8"	Pisces	distance is ~180–290 pc, metallicity is ~0.004 Z_{Sol}. Transitional brown dwarfs.
Least massive	OTS 44	M9.5	$11^h\ 10^m\ 11.5^s$ −76° 32′ 13″	Chamaeleon	Has a mass range of 11.5–15 M_J, distance is ~550 ly
Largest					
Smallest	WISEA 1810−1010	esdT	$18^h\ 10^m\ 06.18^s$−10° 10′ 00.5″	Serpens	Radius is $0.65^{+0.31}_{-0.19}\ R_J$ (~92,400 km)[173]
Fastest rotating	2MASS J03480772−6022270	T7	$03^h48^m07.72^s$ –60°22'27.1"	Reticulum	Rotational period of $1.080^{+0.004}_{-0.005}$

					hours[174]
Farthest	KMT-2016-BLG-2142 b		$17^h\ 52^m\ 27.0^s$ –29° 23′ 04″	Sagittarius	(microlensing)[175] has a distance of 5,850 to 8,020 parsec. Could also be massive gas giant.[176]
Nearest	Luhman 16 AB	L7.5 + T0.5 ± 1	$10^h\ 49^m\ 18.723^s$ −53° 19′ 09.86″	Vela	Distance: ~6.5 ly
Brightest					
Dimmest	L 97-3B	Y1	$08^h\ 06^m\ 53.736^s$ −66° 18′ 16.74″	Volans	jmag=25.42, planetary-mass object
Hottest					
Coolest	WISE 0855−0714[75]	Y4	$08^h\ 55^m\ 10.83^s$ −07° 14′ 42.5″	Hydra	Temperature −48 to −13 °C
Coolest radio-flaring	WISE J062309.94-045624.6	T8	$06^h23^m09.28^s$ −04°56'22.8"	Monoceros	699 K brown dwarf with 4.17 mJy bursts[177]
Most dense	TOI-569b[178]		$07^h\ 40^m\ 24.658^s$ -42° 09′ 16.74″	Puppis	Transiting, has 64.1 M_J with a diameter 0.79 ± 0.02 times that of Jupiter. Density is 171.3g/cm^3.
Least dense					

Gallery



Brown dwarf illustration[179]

See also

- Fusor (astronomy)
- Brown-dwarf desert – Theorized range of orbits around a star within which brown dwarfs cannot exist as companion objects
- Blue dwarf (red-dwarf stage) – Hypothetical class of star that develops from a red dwarf
- Dark matter – Hypothetical form of matter that interacts with gravity, but not with light or electromagnetic field
- Exoplanet – Planet outside the Solar System
- Stellification
- WD 0032-317 b
- List of brown dwarfs

References

1. Sorahana, Satoko; Yamamura, Issei; Murakami, Hiroshi (2013). "On the Radii of Brown Dwarfs Measured with *AKARI* Near-infrared Spectroscopy" (https://doi.org/10.1088%2F0004-637X%2F767%2F1%2F77). *The Astrophysical Journal*. **767** (1): 77. arXiv:1304.1259 (https://arxiv.org/abs/1304.1259). Bibcode:2013ApJ...767...77S (https://ui.adsabs.harvard.edu/abs/2013ApJ...767...77S). doi:10.1088/0004-637X/767/1/77 (https://doi.org/10.1088%2F0004-637X%2F767%2F1%2F77). "We find that the brown dwarf radius ranges between 0.64–1.13 R_J with an average radius of 0.83 R_J."
2. Boss, Alan; McDowell, Tina (April 3, 2001). "Are They Planets or What?" (https://web.archive.org/web/20060928065124/http://www.carnegieinstitution.org/News4-3%2C2001.html). *Untitled Document*. Carnegie Institution of Washington. Archived from the original (http://www.carnegieinstitution.org/News4-3,2001.html) on September 28, 2006. Retrieved March 31, 2022.
3. Wethington, Nicholos (October 6, 2008). "Dense Exoplanet Creates Classification Calamity" (http://www.universetoday.com/19237/dense-exoplanet-creates-classification-calamity/). *Universe Today*. Retrieved March 31, 2022.
4. Burgasser, Adam J. (June 2008). "Brown dwarfs: Failed stars, super Jupiters" (https://web.archive.org/web/20130508182012/http://astro.berkeley.edu/~gmarcy/astro160/papers/brown_dwarfs_failed_stars.pdf) (PDF). *Physics Today*. Cambridge, MA: Massachusetts Institute of Technology. **61** (6): 70–71. Bibcode:2008PhT....61f..70B (https://ui.adsabs.harvard.edu/abs/2008PhT....61f..70B). doi:10.1063/1.2947658 (https://doi.org/10.1063%2F1.2947658). Archived from the original (http://astro.berkeley.edu/~gmarcy/astro160/papers/brown_dwarfs_failed_stars.pdf) (PDF) on May 8, 2013. Retrieved March 31, 2022 – via American Institute of Physics.
5. Springer, Cham (2014). Joergens, Viki (ed.). *50 Years of Brown Dwarfs* (https://link.springer.com/book/10.1007/978-3-319-01162-2#about). Astrophysics and Space Science Library. Vol. 401. SpringerLink. XI, 168. doi:10.1007/978-3-319-01162-2 (https://doi.org/10.1007%2F978-3-319-01162-2). eISSN 2214-7985 (https://www.worldcat.org/issn/2214-7985). ISBN 978-3-319-01162-2. ISSN 0067-0057 (https://www.worldcat.org/issn/0067-0057). Retrieved March 31, 2022.
6. Cain, Fraser (January 6, 2009). "If Brown Isn't a Color, What Color are Brown Dwarfs?" (http://www.universetoday.com/23247/if-brown-isnt-a-color-what-color-are-brown-dwarfs/). Retrieved 24 September 2013.
7. Burrows, Adam; Hubbard, William B.; Lunine, Jonathan I.; Liebert, James (2001). "The Theory of Brown Dwarfs and Extrasolar Giant Planets". *Reviews of Modern Physics*. **73** (3): 719–765. arXiv:astro-ph/0103383 (https://arxiv.org/abs/astro-ph/0103383). Bibcode:2001RvMP...73..719B (https://ui.adsabs.harvard.edu/abs/2001RvMP...73..719B). doi:10.1103/RevModPhys.73.719 (https://doi.org/10.1103%2FRevModPhys.73.719). S2CID 204927572 (https://api.semanticscholar.org/CorpusID:204927572).
8. O'Neill, Ian (13 September 2011). "Violent Storms Rage on Nearby Brown Dwarf" (https://www.seeker.com/violent-storms-rage-on-nearby-brown-dwarf-1765411574.html). Seeker.com.
9. Kumar, Shiv S. (1962). "Study of Degeneracy in Very Light Stars" (https://doi.org/10.1086%2F108658). *Astronomical Journal*. **67**: 579. Bibcode:1962AJ.....67S.579K (https://ui.adsabs.harvard.edu/abs/1962AJ.....67S.579K). doi:10.1086/108658 (https://doi.org/10.1086%2F108658).
10. Tarter, Jill (2014), "Brown is Not a Color: Introduction of the Term 'Brown Dwarf' " (https://www.springer.com/astronomy/book/978-3-319-01161-5), in Joergens, Viki (ed.), *50 Years of Brown Dwarfs – From Prediction to Discovery to Forefront of Research*, Astrophysics and Space Science Library, vol. 401, Springer, pp. 19–24, doi:10.1007/978-3-319-01162-2_3 (https://doi.org/10.1007%2F978-3-319-01162-2_3), ISBN 978-3-319-01162-2
11. Croswell, Ken (1999). *Planet Quest: The Epic Discovery of Alien Solar Systems*. Oxford University Press. pp. 118–119. ISBN 978-0-192-88083-3.
12. "When will the Sun become a black dwarf?" (https://astronomy.com/magazine/ask-astro/2020/04/when-will-the-sun-become-a-black-dwarf). *Astronomy.com*. April 10, 2020. Retrieved 2022-05-02.
13. Kumar, Shiv S. (1963). "The Structure of Stars of Very Low Mass". *Astrophysical Journal*. **137**: 1121. Bibcode:1963ApJ...137.1121K (https://ui.adsabs.harvard.edu/abs/1963ApJ...137.1121K). doi:10.1086/147589 (https://doi.org/10.1086%2F147589).
14. Hayashi, Chushiro; Nakano, Takenori (1963). "Evolution of Stars of Small Masses in the Pre-Main-Sequence Stages" (https://doi.org/10.1143%2FPTP.30.460). *Progress of Theoretical Physics*. **30** (4): 460–474. Bibcode:1963PThPh..30..460H (https://ui.adsabs.harvard.edu/abs/1963PThPh..30..460H). doi:10.1143/PTP.30.460 (https://doi.org/10.1143%2FPTP.30.460).
15. Nakano, Takenori (2014), "Pre-main Sequence Evolution and the Hydrogen-Burning Minimum Mass" (https://www.springer.com/astronomy/book/978-3-319-01161-5), in Joergens, Viki (ed.), *50 Years of Brown Dwarfs – From Prediction to Discovery to Forefront of Research*, Astrophysics and Space Science Library, vol. 401, Springer, pp. 5–17, doi:10.1007/978-3-319-01162-2_2 (https://doi.org/10.1007%2F978-3-319-01162-2_2), ISBN 978-3-319-01162-2, S2CID 73521636 (https://api.semanticscholar.org/CorpusID:73521636)

16. Martín, Eduardo L.; Basri, Gibor; Delfosse, Xavier; Forveille, Thierry (1997). "Keck HIRES spectra of the brown dwarf DENIS-P J1228.2-1547". *Astronomy and Astrophysics*. **327**: L29–L32. Bibcode:1997A&A...327L..29M (https://ui.adsabs.harvard.edu/abs/1997A&A...327L..29M).
17. Kirkpatrick, J. Davy; Reid, I. Neill; Liebert, James; Cutri, Roc M.; Nelson, Brant; Beichmann, Charles A.; Dahn, Conard C.; Monet, David G.; Gizis, John E.; Skrutskie, Michael F. (1999). "Dwarfs Cooler than *M*: The Definition of Spectral Type *L* Using Discoveries from the 2 Micron All-Sky Survey (2MASS)" (https://trs.jpl.nasa.gov/bitstream/2014/37403/1/99-0060.pdf) (PDF). *The Astrophysical Journal*. **519** (2): 802–833. Bibcode:1999ApJ...519..802K (https://ui.adsabs.harvard.edu/abs/1999ApJ...519..802K). doi:10.1086/307414 (https://doi.org/10.1086%2F307414). S2CID 73569208 (https://api.semanticscholar.org/CorpusID:73569208).
18. "Astronomers Announce First Clear Evidence of a Brown Dwarf" (https://hubblesite.org/contents/news-releases/1995/news-1995-48.html). *STScI*. Retrieved 2019-10-23.
19. "Instituto de Astrofísica de Canarias, IAC" (http://www.iac.es/). Iac.es. Retrieved 2013-03-16.
20. Rebolo, Rafael (2014), "Teide 1 and the Discovery of Brown Dwarfs" (https://www.springer.com/astronomy/book/978-3-319-01161-5), in Joergens, Viki (ed.), *50 Years of Brown Dwarfs – From Prediction to Discovery to Forefront of Research*, Astrophysics and Space Science Library, vol. 401, Springer, pp. 25–50, doi:10.1007/978-3-319-01162-2_4 (https://doi.org/10.1007%2F978-3-319-01162-2_4), ISBN 978-3-319-01162-2
21. Rebolo, Rafael; Zapatero-Osorio, María Rosa; Martín, Eduardo L. (September 1995). "Discovery of a brown dwarf in the Pleiades star cluster". *Nature*. **377** (6545): 129–131. Bibcode:1995Natur.377..129R (https://ui.adsabs.harvard.edu/abs/1995Natur.377..129R). doi:10.1038/377129a0 (https://doi.org/10.1038%2F377129a0). S2CID 28029538 (https://api.semanticscholar.org/CorpusID:28029538).
22. Leech, Kieron; Altieri, Bruno; Metcalfe, Liam; Martin, Eduardo L.; Rebolo, Rafael; Zapatero-Osorio, María Rosa; Laureijs, René J.; Prusti, Timo; Salama, Alberto; Siebenmorgen, Ralf; Claes, Peter; Trams, Norman (2000). "Mid-IR Observations of the Pleiades Brown Dwarfs Teide 1 & Calar 3". *ASP Conference Series*. **212**: 82–87. Bibcode:2000ASPC..212...82L (https://ui.adsabs.harvard.edu/abs/2000ASPC..212...82L).
23. Kirkpatrick, J. Davy; Burgasser, Adam J. (6 November 2012). "Photometry, spectroscopy, and astrometry of M, L, and T dwarfs" (http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/index.shtml). *DwarfArchives.org*. Pasadena, CA: California Institute of Technology. Retrieved 2012-12-28. (M=536, L=918, T=355, Y=14)
24. McCaughrean, Mark J.; Close, Laird M.; Scholz, Ralf-Dieter; Lenzen, Rainer; Biller, Beth A.; Brandner, Wolfgang; Hartung, Markus; Lodieu, Nicolas (January 2004). "Epsilon Indi Ba/Bb: the nearest binary brown dwarf". *Astronomy & Astrophysics*. **413** (3): 1029–1036. arXiv:astro-ph/0309256 (https://arxiv.org/abs/astro-ph/0309256). doi:10.1051/0004-6361:20034292 (https://doi.org/10.1051%2F0004-6361%3A20034292). S2CID 15407249 (https://api.semanticscholar.org/CorpusID:15407249).
25. Forbes, John C.; Loeb, Abraham (February 2019), "On the Existence of Brown Dwarfs More Massive than the Hydrogen Burning Limit", *The Astrophysical Journal*, **871** (2): 11, arXiv:1805.12143 (https://arxiv.org/abs/1805.12143), Bibcode:2019ApJ...871..227F (https://ui.adsabs.harvard.edu/abs/2019ApJ...871..227F), doi:10.3847/1538-4357/aafac8 (https://doi.org/10.3847%2F1538-4357%2Faafac8), S2CID 119059288 (https://api.semanticscholar.org/CorpusID:119059288), 227
26. Burrows, Adam; Hubbard, W. B.; Lunine, J. I.; Liebert, James (July 2001). "The theory of brown dwarfs and extrasolar giant planets". *Reviews of Modern Physics*. **73** (3): 719–765. arXiv:astro-ph/0103383 (https://arxiv.org/abs/astro-ph/0103383). Bibcode:2001RvMP...73..719B (https://ui.adsabs.harvard.edu/abs/2001RvMP...73..719B). doi:10.1103/RevModPhys.73.719 (https://doi.org/10.1103%2FRevModPhys.73.719). S2CID 204927572 (https://api.semanticscholar.org/CorpusID:204927572). "Hence the HBMM at solar metallicity and Y_{α} = 50.25 is 0.07 – 0.074 $M_{\odot}$, ... while the HBMM at zero metallicity is 0.092 $M_{\odot}$"
27. Kulkarni, Shrinivas R. (30 May 1997). "Brown Dwarfs: A Possible Missing Link Between Stars and Planets". *Science*. **276** (5317): 1350–1354. Bibcode:1997Sci...276.1350K (https://ui.adsabs.harvard.edu/abs/1997Sci...276.1350K). doi:10.1126/science.276.5317.1350 (https://doi.org/10.1126%2Fscience.276.5317.1350).
28. Burgasser, Adam J.; Marley, Mark S.; Ackerman, Andrew S.; Saumon, Didier; Lodders, Katharina; Dahn, Conard C.; Harris, Hugh C.; Kirkpatrick, J. Davy (2002-06-01). "Evidence of Cloud Disruption in the L/T Dwarf Transition" (https://doi.org/10.1086%2F341343). *The Astrophysical Journal*. **571** (2): L151–L154. arXiv:astro-ph/0205051 (https://arxiv.org/abs/astro-ph/0205051). Bibcode:2002ApJ...571L.151B (https://ui.adsabs.harvard.edu/abs/2002ApJ...571L.151B). doi:10.1086/341343 (https://doi.org/10.1086%2F341343). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).

29. Vos, Johanna M.; Faherty, Jacqueline K.; Gagné, Jonathan; Marley, Mark; Metchev, Stanimir; Gizis, John; Rice, Emily L.; Cruz, Kelle (2022-01-01). "Let the Great World Spin: Revealing the Stormy, Turbulent Nature of Young Giant Exoplanet Analogs with the Spitzer Space Telescope" (https://doi.org/10.3847%2F1538-4357%2Fac4502). *The Astrophysical Journal*. **924** (2): 68. arXiv:2201.04711 (https://arxiv.org/abs/2201.04711). Bibcode:2022ApJ...924...68V (https://ui.adsabs.harvard.edu/abs/2022ApJ...924...68V). doi:10.3847/1538-4357/ac4502 (https://doi.org/10.3847%2F1538-4357%2Fac4502). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
30. Vos, Johanna M.; Burningham, Ben; Faherty, Jacqueline K.; Alejandro, Sherelyn; Gonzales, Eileen; Calamari, Emily; Bardalez Gagliuffi, Daniella; Visscher, Channon; Tan, Xianyu; Morley, Caroline V.; Marley, Mark; Gemma, Marina E.; Whiteford, Niall; Gaarn, Josefine; Park, Grace (2023-02-01). "Patchy Forsterite Clouds in the Atmospheres of Two Highly Variable Exoplanet Analogs" (https://doi.org/10.3847%2F1538-4357%2Facab58). *The Astrophysical Journal*. **944** (2): 138. arXiv:2212.07399 (https://arxiv.org/abs/2212.07399). Bibcode:2023ApJ...944..138V (https://ui.adsabs.harvard.edu/abs/2023ApJ...944..138V). doi:10.3847/1538-4357/acab58 (https://doi.org/10.3847%2F1538-4357%2Facab58). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
31. Manjavacas, Elena; Karalidi, Theodora; Vos, Johanna M.; Biller, Beth A.; Lew, Ben W. P. (2021-11-01). "Revealing the Vertical Cloud Structure of a Young Low-mass Brown Dwarf, an Analog to the β-Pictoris b Directly Imaged Exoplanet, through Keck I/MOSFIRE Spectrophotometric Variability" (https://doi.org/10.3847%2F1538-3881%2Fac174c). *The Astronomical Journal*. **162** (5): 179. arXiv:2107.12368 (https://arxiv.org/abs/2107.12368). Bibcode:2021AJ....162..179M (https://ui.adsabs.harvard.edu/abs/2021AJ....162..179M). doi:10.3847/1538-3881/ac174c (https://doi.org/10.3847%2F1538-3881%2Fac174c). ISSN 0004-6256 (https://www.worldcat.org/issn/0004-6256).
32. Tremblin, P.; Chabrier, G.; Baraffe, I.; Liu, Michael. C.; Magnier, E. A.; Lagage, P. -O.; Alves de Oliveira, C.; Burgasser, A. J.; Amundsen, D. S.; Drummond, B. (2017-11-01). "Cloudless Atmospheres for Young Low-gravity Substellar Objects" (https://doi.org/10.3847%2F1538-4357%2Faa9214). *The Astrophysical Journal*. **850** (1): 46. arXiv:1710.02640 (https://arxiv.org/abs/1710.02640). Bibcode:2017ApJ...850...46T (https://ui.adsabs.harvard.edu/abs/2017ApJ...850...46T). doi:10.3847/1538-4357/aa9214 (https://doi.org/10.3847%2F1538-4357%2Faa9214). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
33. Suárez, Genaro; Metchev, Stanimir (2022-07-01). "Ultracool dwarfs observed with the Spitzer infrared spectrograph - II. Emergence and sedimentation of silicate clouds in L dwarfs, and analysis of the full M5-T9 field dwarf spectroscopic sample" (https://ui.adsabs.harvard.edu/abs/2022MNRAS.513.5701S). *Monthly Notices of the Royal Astronomical Society*. **513** (4): 5701–5726. arXiv:2205.00168 (https://arxiv.org/abs/2205.00168). Bibcode:2022MNRAS.513.5701S (https://ui.adsabs.harvard.edu/abs/2022MNRAS.513.5701S). doi:10.1093/mnras/stac1205 (https://doi.org/10.1093%2Fmnras%2Fstac1205). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711).
34. Miles, Brittany E.; Biller, Beth A.; Patapis, Polychronis; Worthen, Kadin; Rickman, Emily; Hoch, Kielan K. W.; Skemer, Andrew; Perrin, Marshall D.; Whiteford, Niall; Chen, Christine H.; Sargent, B.; Mukherjee, Sagnick; Morley, Caroline V.; Moran, Sarah E.; Bonnefoy, Mickael (2023-03-01). "The JWST Early-release Science Program for Direct Observations of Exoplanetary Systems II: A 1 to 20 μm Spectrum of the Planetary-mass Companion VHS 1256-1257 b" (https://doi.org/10.3847%2F2041-8213%2Facb04a). *The Astrophysical Journal*. **946** (1): L6. arXiv:2209.00620 (https://arxiv.org/abs/2209.00620). Bibcode:2023ApJ...946L...6M (https://ui.adsabs.harvard.edu/abs/2023ApJ...946L...6M). doi:10.3847/2041-8213/acb04a (https://doi.org/10.3847%2F2041-8213%2Facb04a). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
35. Biller, Beth A.; Crossfield, Ian J. M.; Mancini, Luigi; Ciceri, Simona; Southworth, John; Kopytova, Taisiya G.; Bonnefoy, Mickaël; Deacon, Niall R.; Schlieder, Joshua E.; Buenzli, Esther; Brandner, Wolfgang; Allard, France; Homeier, Derek; Freytag, Bernd; Bailer-Jones, Coryn A. L.; Greiner, Jochen; Henning, Thomas; Goldman, Bertrand (6 November 2013). "Weather on the Nearest Brown Dwarfs: Resolved Simultaneous Multi-Wavelength Variability Monitoring of WISE J104915.57–531906.1AB". *The Astrophysical Journal Letters*. **778** (1): L10. arXiv:1310.5144 (https://arxiv.org/abs/1310.5144). Bibcode:2013ApJ...778L..10B (https://ui.adsabs.harvard.edu/abs/2013ApJ...778L..10B). doi:10.1088/2041-8205/778/1/l10 (https://doi.org/10.1088%2F2041-8205%2F778%2F1%2Fl10). S2CID 56107487 (https://api.semanticscholar.org/CorpusID:56107487).
36. Morley, Caroline V.; Fortney, Jonathan J.; Marley, Mark S.; Visscher, Channon; Saumon, Didier; Leggett, S. K. (2012-09-01). "Neglected Clouds in T and Y Dwarf Atmospheres" (https://ui.adsabs.harvard.edu/abs/2012ApJ...756..172M). *The Astrophysical Journal*. **756** (2): 172. arXiv:1206.4313 (https://arxiv.org/abs/1206.4313). Bibcode:2012ApJ...756..172M (https://ui.adsabs.harvard.edu/abs/2012ApJ...756..172M). doi:10.1088/0004-637X/756/2/172 (https://doi.org/10.1088%2F0004-637X%2F756%2F2%2F172). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 118398946 (https://api.semanticscholar.org/CorpusID:118398946).

37. Manjavacas, Elena; Karalidi, Theodora; Tan, Xianyu; Vos, Johanna M.; Lew, Ben W. P.; Biller, Beth A.; Oliveros-Gómez, Natalia (2022-08-01). "Top-of-the-atmosphere and Vertical Cloud Structure of a Fast-rotating Late T Dwarf" (https://doi.org/10.3847%2F1538-3881%2Fac7953). *The Astronomical Journal*. **164** (2): 65. arXiv:2206.07566 (https://arxiv.org/abs/2206.07566). Bibcode:2022AJ....164...65M (https://ui.adsabs.harvard.edu/abs/2022AJ....164...65M). doi:10.3847/1538-3881/ac7953 (https://doi.org/10.3847%2F1538-3881%2Fac7953). ISSN 0004-6256 (https://www.worldcat.org/issn/0004-6256).
38. Faherty, Jacqueline K.; Tinney, C. G.; Skemer, Andrew; Monson, Andrew J. (2014-09-01). "Indications of Water Clouds in the Coldest Known Brown Dwarf" (https://ui.adsabs.harvard.edu/abs/2014ApJ...793L..16F). *The Astrophysical Journal*. **793** (1): L16. arXiv:1408.4671 (https://arxiv.org/abs/1408.4671). Bibcode:2014ApJ...793L..16F (https://ui.adsabs.harvard.edu/abs/2014ApJ...793L..16F). doi:10.1088/2041-8205/793/1/L16 (https://doi.org/10.1088%2F2041-8205%2F793%2F1%2FL16). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 119246100 (https://api.semanticscholar.org/CorpusID:119246100).
39. Basri, Gibor; Brown, Michael E. (2006-08-20). "Planetesimals to Brown Dwarfs: What is a Planet?". *Annual Review of Earth and Planetary Sciences*. **34** (2006): 193–216. arXiv:astro-ph/0608417 (https://arxiv.org/abs/astro-ph/0608417). Bibcode:2006AREPS..34..193B (https://ui.adsabs.harvard.edu/abs/2006AREPS..34..193B). doi:10.1146/annurev.earth.34.031405.125058 (https://doi.org/10.1146%2Fannurev.earth.34.031405.125058). S2CID 119338327 (https://api.semanticscholar.org/CorpusID:119338327).
40. Chen, Jingjing; Kipping, David (2016). "Probabilistic Forecasting of the Masses and Radii of Other Worlds" (https://doi.org/10.3847%2F1538-4357%2F834%2F1%2F17). *The Astrophysical Journal*. **834** (1): 17. arXiv:1603.08614 (https://arxiv.org/abs/1603.08614). doi:10.3847/1538-4357/834/1/17 (https://doi.org/10.3847%2F1538-4357%2F834%2F1%2F17). S2CID 119114880 (https://api.semanticscholar.org/CorpusID:119114880).
41. "The Jovian Planets: Uranus, and Neptune" (https://web.archive.org/web/20120118184803/http://astronomy.nmsu.edu/tharriso/ast105/UranusandNeptune.html). Archived from the original (http://astronomy.nmsu.edu/tharriso/ast105/UranusandNeptune.html) on 2012-01-18. Retrieved 2013-03-15.
42. "Cool Cosmos – Planets and Moons" (https://web.archive.org/web/20190221171452/http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/planets.html). Archived from the original (http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/planets.html) on 2019-02-21. Retrieved 2019-02-11.
43. "Working Group on Extrasolar Planets: Definition of a "Planet" " (https://web.archive.org/web/20141216075559/http://home.dtm.ciw.edu/users/boss/definition.html). *IAU position statement*. 2003-02-28. Archived from the original (http://home.dtm.ciw.edu/users/boss/definition.html) on 2014-12-16. Retrieved 2014-04-28.
44. Bodenheimer, Peter; D'Angelo, Gennaro; Lissauer, Jack J.; Fortney, Jonathan J.; Saumon, Didier (2013). "Deuterium Burning in Massive Giant Planets and Low-mass Brown Dwarfs Formed by Core-nucleated Accretion". *The Astrophysical Journal*. **770** (2): 120 (13 pp.). arXiv:1305.0980 (https://arxiv.org/abs/1305.0980). Bibcode:2013ApJ...770..120B (https://ui.adsabs.harvard.edu/abs/2013ApJ...770..120B). doi:10.1088/0004-637X/770/2/120 (https://doi.org/10.1088%2F0004-637X%2F770%2F2%2F120). S2CID 118553341 (https://api.semanticscholar.org/CorpusID:118553341).
45. Spiegel, David S.; Burrows, Adam; Milson, John A. (2011). "The Deuterium-Burning Mass Limit for Brown Dwarfs and Giant Planets". *The Astrophysical Journal*. **727** (1): 57. arXiv:1008.5150 (https://arxiv.org/abs/1008.5150). Bibcode:2011ApJ...727...57S (https://ui.adsabs.harvard.edu/abs/2011ApJ...727...57S). doi:10.1088/0004-637X/727/1/57 (https://doi.org/10.1088%2F0004-637X%2F727%2F1%2F57). S2CID 118513110 (https://api.semanticscholar.org/CorpusID:118513110).
46. Schneider, Jean; Dedieu, Cyril; Le Sidaner, Pierre; Savalle, Renaud; Zolotukhin, Ivan (2011). "Defining and cataloging exoplanets: The exoplanet.eu database". *Astronomy & Astrophysics*. **532** (79): A79. arXiv:1106.0586 (https://arxiv.org/abs/1106.0586). Bibcode:2011A&A...532A..79S (https://ui.adsabs.harvard.edu/abs/2011A&A...532A..79S). doi:10.1051/0004-6361/201116713 (https://doi.org/10.1051%2F0004-6361%2F201116713). S2CID 55994657 (https://api.semanticscholar.org/CorpusID:55994657).
47. Schneider, Jean (July 2016). "Exoplanets versus brown dwarfs: the CoRoT view and the future". *The CoRoT Legacy Book*. p. 157. arXiv:1604.00917 (https://arxiv.org/abs/1604.00917). doi:10.1051/978-2-7598-1876-1.c038 (https://doi.org/10.1051%2F978-2-7598-1876-1.c038). ISBN 978-2-7598-1876-1. S2CID 118434022 (https://api.semanticscholar.org/CorpusID:118434022).
48. Hatzes, Artie P.; Rauer, Heike (2015). "A Definition for Giant Planets Based on the Mass-Density Relationship". *The Astrophysical Journal*. **810** (2): L25. arXiv:1506.05097 (https://arxiv.org/abs/1506.05097). Bibcode:2015ApJ...810L..25H (https://ui.adsabs.harvard.edu/abs/2015ApJ...810L..25H). doi:10.1088/2041-8205/810/2/L25 (https://doi.org/10.1088%2F2041-8205%2F810%2F2%2FL25). S2CID 119111221 (https://api.semanticscholar.org/CorpusID:119111221).

49. Wright, Jason T.; Fakhouri, Onsi; Marcy, Geoffrey W.; Han, Eunkyu; Feng, Y. Katherina; Johnson, John Asher; Howard, Andrew W.; Fischer, Debra A.; Valenti, Jeff A.; Anderson, Jay; Piskunov, Nikolai (2010). "The Exoplanet Orbit Database". *Publications of the Astronomical Society of the Pacific*. **123** (902): 412–422. arXiv:1012.5676 (https://arxiv.org/abs/1012.5676). Bibcode:2011PASP..123..412W (https://ui.adsabs.harvard.edu/abs/2011PASP..123..412W). doi:10.1086/659427 (https://doi.org/10.1086%2F659427). S2CID 51769219 (https://api.semanticscholar.org/CorpusID:51769219).
50. Exoplanet Criteria for Inclusion in the Archive (http://exoplanetarchive.ipac.caltech.edu/docs/exoplanet_criteria.html), NASA Exoplanet Archive
51. Working Group on Extrasolar Planets – Definition of a "Planet" (http://www.dtm.ciw.edu/boss/definition.html) Archived (https://web.archive.org/web/20120702204018/http://www.dtm.ciw.edu/boss/definition.html) 2012-07-02 at the Wayback Machine Position statement on the definition of a "planet" (IAU)
52. Delorme, Philippe; Gagné, Jonathan; Malo, Lison; Reylé, Céline; Artigau, Étienne; Albert, Loïc; Forveille, Thierry; Delfosse, Xavier; Allard, France; Homeier, Derek (December 2012). "CFBDSIR2149-0403: a 4–7 Jupiter-mass free-floating planet in the young moving group AB Doradus?". *Astronomy & Astrophysics*. **548**: A26. arXiv:1210.0305 (https://arxiv.org/abs/1210.0305). Bibcode:2012A&A...548A..26D (https://ui.adsabs.harvard.edu/abs/2012A&A...548A..26D). doi:10.1051/0004-6361/201219984 (https://doi.org/10.1051%2F0004-6361%2F201219984). S2CID 50935950 (https://api.semanticscholar.org/CorpusID:50935950).
53. Luhman, Kevin L. (21 April 2014). "Discovery of a ~250 K Brown Dwarf at 2 pc from the Sun". *The Astrophysical Journal Letters*. **786** (2): L18. arXiv:1404.6501 (https://arxiv.org/abs/1404.6501). Bibcode:2014ApJ...786L..18L (https://ui.adsabs.harvard.edu/abs/2014ApJ...786L..18L). doi:10.1088/2041-8205/786/2/L18 (https://doi.org/10.1088%2F2041-8205%2F786%2F2%2FL18). S2CID 119102654 (https://api.semanticscholar.org/CorpusID:119102654).
54. Saumon, Didier; Marley, Mark S. (December 2008). "The Evolution of L and T Dwarfs in Color-Magnitude Diagrams". *Astrophysical Journal*. **689** (2): 1327–1344. arXiv:0808.2611 (https://arxiv.org/abs/0808.2611). Bibcode:2008ApJ...689.1327S (https://ui.adsabs.harvard.edu/abs/2008ApJ...689.1327S). doi:10.1086/592734 (https://doi.org/10.1086%2F592734). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 15981010 (https://api.semanticscholar.org/CorpusID:15981010).
55. Marocco, Federico; Kirkpatrick, J. Davy; Meisner, Aaron M.; Caselden, Dan; Eisenhardt, Peter R. M.; Cushing, Michael C.; Faherty, Jacqueline K.; Gelino, Christopher R.; Wright, Edward L. (2020). "Improved infrared photometry and a preliminary parallax measurement for the extremely cold brown dwarf CWISEP J144606.62-231717.8" (https://doi.org/10.3847%2F2041-8213%2Fab6201). *The Astrophysical Journal*. **888** (2): L19. arXiv:1912.07692 (https://arxiv.org/abs/1912.07692). Bibcode:2020ApJ...888L..19M (https://ui.adsabs.harvard.edu/abs/2020ApJ...888L..19M). doi:10.3847/2041-8213/ab6201 (https://doi.org/10.3847%2F2041-8213%2Fab6201). S2CID 209386563 (https://api.semanticscholar.org/CorpusID:209386563).
56. Filippazzo, Joseph C.; Rice, Emily L.; Faherty, Jacqueline K.; Cruz, Kelle L.; Van Gordon, Mollie M.; Looper, Dagny L. (September 2015). "Fundamental Parameters and Spectral Energy Distributions of Young and Field Age Objects with Masses Spanning the Stellar to Planetary Regime". *Astrophysical Journal*. **810** (2): 158. arXiv:1508.01767 (https://arxiv.org/abs/1508.01767). Bibcode:2015ApJ...810..158F (https://ui.adsabs.harvard.edu/abs/2015ApJ...810..158F). doi:10.1088/0004-637X/810/2/158 (https://doi.org/10.1088%2F0004-637X%2F810%2F2%2F158). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 89611607 (https://api.semanticscholar.org/CorpusID:89611607).
57. Mohanty, Subhanjoy; Jayawardhana, Ray; Huélamo, Nuria; Mamajek, Eric (March 2007). "The Planetary Mass Companion 2MASS 1207-3932B: Temperature, Mass, and Evidence for an Edge-on Disk". *Astrophysical Journal*. **657** (2): 1064–1091. arXiv:astro-ph/0610550 (https://arxiv.org/abs/astro-ph/0610550). Bibcode:2007ApJ...657.1064M (https://ui.adsabs.harvard.edu/abs/2007ApJ...657.1064M). doi:10.1086/510877 (https://doi.org/10.1086%2F510877). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 17326111 (https://api.semanticscholar.org/CorpusID:17326111).
58. Zhang, Zhoujian; Liu, Michael C.; Hermes, James J.; Magnier, Eugene A.; Marley, Mark S.; Tremblay, Pier-Emmanuel; Tucker, Michael A.; Do, Aaron; Payne, Anna V.; Shappee, Benjamin J. (February 2020). "COol Companions ON Ultrawide orbiTS (COCONUTS). I. A High-Gravity T4 Benchmark around an Old White Dwarf and A Re-Examination of the Surface-Gravity Dependence of the L/T Transition" (https://doi.org/10.3847%2F1538-4357%2Fab765c). *The Astrophysical Journal*. **891** (2): 171. arXiv:2002.05723 (https://arxiv.org/abs/2002.05723). Bibcode:2020ApJ...891..171Z (https://ui.adsabs.harvard.edu/abs/2020ApJ...891..171Z). doi:10.3847/1538-4357/ab765c (https://doi.org/10.3847%2F1538-4357%2Fab765c). S2CID 211126544 (https://api.semanticscholar.org/CorpusID:211126544).

59. Smart, Richard L.; Bucciarelli, Beatrice; Jones, Hugh R. A.; Marocco, Federico; Andrei, Alexandre Humberto; Goldman, Bertrand; Méndez, René A.; d'Avila, Victor de A.; Burningham, Ben; Camargo, Julio Ignácio Bueno de; Crosta, Maria Teresa; Daprà, Mario; Jenkins, James S.; Lachaume, Regis; Lattanzi, Mario G.; Penna, Jucira L.; Pinfield, David J.; da Silva Neto, Dario Nepomuceno; Sozzetti, Alessandro; Vecchiato, Alberto (December 2018). "Parallaxes of Southern Extremely Cool objects III: 118 L and T dwarfs". *MNRAS*. **481** (3): 3548–3562. arXiv:1811.00672 (https://arxiv.org/abs/1811.00672). Bibcode:2018MNRAS.481.3548S (https://ui.adsabs.harvard.edu/abs/2018MNRAS.481.3548S). doi:10.1093/mnras/sty2520 (https://doi.org/10.1093%2Fmnras%2Fsty2520). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 119390019 (https://api.semanticscholar.org/CorpusID:119390019).
60. Burrows, Adam; Hubbard, William B.; Lunine, Jonathan I.; Liebert, James (2001). "The theory of brown dwarfs and extrasolar giant planets". *Reviews of Modern Physics*. **73** (3): 719–765. arXiv:astro-ph/0103383 (https://arxiv.org/abs/astro-ph/0103383). Bibcode:2001RvMP...73..719B (https://ui.adsabs.harvard.edu/abs/2001RvMP...73..719B). doi:10.1103/RevModPhys.73.719 (https://doi.org/10.1103%2FRevModPhys.73.719). S2CID 204927572 (https://api.semanticscholar.org/CorpusID:204927572).
61. "An Artist's View of Brown Dwarf Types" (http://spider.ipac.caltech.edu/staff/davy/2mass/science/comparison.html) Archived (https://web.archive.org/web/20111117180311/http://spider.ipac.caltech.edu/staff/davy/2mass/science/comparison.html) 2011-11-17 at the Wayback Machine
62. Leggett, Sandy K.; Cushing, Michael C.; Saumon, Didier; Marley, Mark S.; Roellig, Thomas L.; Warren, Stephen J.; Burningham, Ben; Jones, Hugh R. A.; Kirkpatrick, J. Davy; Lodieu, Nicolas; Lucas, Philip W.; Mainzer, Amy K.; Martín, Eduardo L.; McCaughrean, Mark J.; Pinfield, David J.; Sloan, Gregory C.; Smart, Richard L.; Tamura, Motohide; Van Cleve, Jeffrey (2009). "The Physical Properties of Four ~600 K T Dwarfs". *The Astrophysical Journal*. **695** (2): 1517–1526. arXiv:0901.4093 (https://arxiv.org/abs/0901.4093). Bibcode:2009ApJ...695.1517L (https://ui.adsabs.harvard.edu/abs/2009ApJ...695.1517L). doi:10.1088/0004-637X/695/2/1517 (https://doi.org/10.1088%2F0004-637X%2F695%2F2%2F1517). S2CID 44050900 (https://api.semanticscholar.org/CorpusID:44050900)..
63. Delorme, Philippe; Delfosse, Xavier; Albert, Loïc; Artigau, Étienne; Forveille, Thierry; Reylé, Céline; Allard, France; Homeier, Derek; Robin, Annie C.; Willott, Chris J.; Liu, Michael C.; Dupuy, Trent J. (2008). "CFBDS J005910.90-011401.3: Reaching the T–Y brown dwarf transition?". *Astronomy and Astrophysics*. **482** (3): 961–971. arXiv:0802.4387 (https://arxiv.org/abs/0802.4387). Bibcode:2008A&A...482..961D (https://ui.adsabs.harvard.edu/abs/2008A&A...482..961D). doi:10.1051/0004-6361:20079317 (https://doi.org/10.1051%2F0004-6361%3A20079317). S2CID 847552 (https://api.semanticscholar.org/CorpusID:847552).
64. Burningham, Ben; Pinfield, David J.; Leggett, Sandy K.; Tamura, Motohide; Lucas, Philip W.; Homeier, Derek; Day-Jones, Avril; Jones, Hugh R. A.; Clarke, J. R. A.; Ishii, Miki; Kuzuhara, Masayuki; Lodieu, Nicolas; Zapatero-Osorio, María Rosa; Venemans, Bram Pieter; Mortlock, Daniel J.; Barrado y Navascués, David; Martín, Eduardo L.; Magazzù, Antonio (2008). "Exploring the substellar temperature regime down to ~550K". *Monthly Notices of the Royal Astronomical Society*. **391** (1): 320–333. arXiv:0806.0067 (https://arxiv.org/abs/0806.0067). Bibcode:2008MNRAS.391..320B (https://ui.adsabs.harvard.edu/abs/2008MNRAS.391..320B). doi:10.1111/j.1365-2966.2008.13885.x (https://doi.org/10.1111%2Fj.1365-2966.2008.13885.x). S2CID 1438322 (https://api.semanticscholar.org/CorpusID:1438322).
65. Beiler, Samuel A.; Cushing, Michael C.; Kirkpatrick, J. Davy; Schneider, Adam C.; Mukherjee, Sagnick; Marley, Mark S. (2023-07-01). "The First JWST Spectral Energy Distribution of a Y Dwarf" (https://doi.org/10.3847%2F2041-8213%2Face32c). *The Astrophysical Journal*. **951** (2): L48. arXiv:2306.11807 (https://arxiv.org/abs/2306.11807). Bibcode:2023ApJ...951L..48B (https://ui.adsabs.harvard.edu/abs/2023ApJ...951L..48B). doi:10.3847/2041-8213/ace32c (https://doi.org/10.3847%2F2041-8213%2Face32c). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
66. Leggett, S. K.; Tremblin, Pascal (25 Sep 2023). "The First Y Dwarf Data From JWST Show That Dynamic and Diabatic Processes Regulate Cold Brown Dwarf Atmospheres" (https://doi.org/10.3847%2F1538-4357%2Facfdad). *ApJ*. **959** (2): 86. arXiv:2309.14567 (https://arxiv.org/abs/2309.14567). Bibcode:2023ApJ...959...86L (https://ui.adsabs.harvard.edu/abs/2023ApJ...959...86L). doi:10.3847/1538-4357/acfdad (https://doi.org/10.3847%2F1538-4357%2Facfdad).
67. Eisenhardt, Peter R. M.; Griffith, Roger L.; Stern, Daniel; Wright, Edward L.; Ashby, Matthew L. N.; Brodwin, Mark; Brown, Michael J. I.; Bussmann, R. S.; Dey, Arjun; Ghez, Andrea Mia; Glikman, Eilat; Gonzalez, Anthony H.; Kirkpatrick, J. Davy; Konopacky, Quinn; Mainzer, Amy; Vollbach, David; Wright, Shelley A. (2010). "Ultracool Field Brown Dwarf Candidates Selected at 4.5 microns". *The Astronomical Journal*. **139** (6): 2455. arXiv:1004.1436 (https://arxiv.org/abs/1004.1436). Bibcode:2010AJ....139.2455E (https://ui.adsabs.harvard.edu/abs/2010AJ....139.2455E). doi:10.1088/0004-6256/139/6/2455 (https://doi.org/10.1088%2F0004-6256%2F139%2F6%2F2455). S2CID 2019463 (https://api.semanticscholar.org/CorpusID:2019463).

68. Luhman, Kevin L.; Burgasser, Adam J.; Bochanski, John J. (20 March 2011). "Discovery of a candidate for the coolest known brown dwarf". *The Astrophysical Journal Letters*. **730** (1): L9. arXiv:1102.5411 (https://arxiv.org/abs/1102.5411). Bibcode:2011ApJ...730L...9L (https://ui.adsabs.harvard.edu/abs/2011ApJ...730L...9L). doi:10.1088/2041-8205/730/1/L9 (https://doi.org/10.1088%2F2041-8205%2F730%2F1%2FL9). S2CID 54666396 (https://api.semanticscholar.org/CorpusID:54666396).
69. Rodriguez, David R.; Zuckerman, Benjamin; Melis, Carl; Song, Inseok (10 May 2011). "The ultra cool brown dwarf companion of WD 0806-661B: age, mass, and formation mechanism". *The Astrophysical Journal*. **732** (2): L29. arXiv:1103.3544 (https://arxiv.org/abs/1103.3544). Bibcode:2011ApJ...732L..29R (https://ui.adsabs.harvard.edu/abs/2011ApJ...732L..29R). doi:10.1088/2041-8205/732/2/L29 (https://doi.org/10.1088%2F2041-8205%2F732%2F2%2FL29). S2CID 118382542 (https://api.semanticscholar.org/CorpusID:118382542).
70. Liu, Michael C.; Delorme, Philippe; Dupuy, Trent J.; Bowler, Brendan P.; Albert, Loïc; Artigau, Étienne; Reylé, Céline; Forveille, Thierry; Delfosse, Xavier (28 Feb 2011). "CFBDSIR J1458+1013B: A Very Cold (>T10) Brown Dwarf in a Binary System". *The Astrophysical Journal*. **740** (2): 108. arXiv:1103.0014 (https://arxiv.org/abs/1103.0014). Bibcode:2011ApJ...740..108L (https://ui.adsabs.harvard.edu/abs/2011ApJ...740..108L). doi:10.1088/0004-637X/740/2/108 (https://doi.org/10.1088%2F0004-637X%2F740%2F2%2F108). S2CID 118344589 (https://api.semanticscholar.org/CorpusID:118344589).
71. Plait, Phil (24 August 2011). "WISE finds coolest brown dwarfs ever seen!" (https://web.archive.org/web/20140726133222/http://blogs.discovermagazine.com/badastronomy/2011/08/24/wise-finds-coolest-brown-dwarfs-ever-seen/#.UnGKkHDkudE). *Discover Magazine*. Archived from the original (http://blogs.discovermagazine.com/badastronomy/2011/08/24/wise-finds-coolest-brown-dwarfs-ever-seen/#.UnGKkHDkudE) on 26 July 2014. Retrieved 30 October 2013.
72. Clavin, Whitney (8 June 2012). "WISE Finds Few Brown Dwarfs Close To Home" (https://web.archive.org/web/20140315070839/http://www.nasa.gov/mission_pages/WISE/news/wise20120608.html). *NASA*. Archived from the original (http://www.nasa.gov/mission_pages/WISE/news/wise20120608.html) on 15 March 2014. Retrieved 30 October 2013.
73. Morse, Jon. "Discovered: Stars as Cool as the Human Body" (https://web.archive.org/web/20111007124027/http://science.nasa.gov/science-news/science-at-nasa/2011/23aug_coldeststars/). Archived from the original (https://science.nasa.gov/science-news/science-at-nasa/2011/23aug_coldeststars/) on 7 October 2011. Retrieved 24 August 2011.
74. Beichman, Charles A.; Gelino, Christopher R.; Kirkpatrick, J. Davy; Barman, Travis S.; Marsh, Kenneth A.; Cushing, Michael C.; Wright, Edward L. (2013). "The Coldest Brown Dwarf (or Free-floating Planet)?: The Y Dwarf WISE 1828+2650". *The Astrophysical Journal*. **764** (1): 101. arXiv:1301.1669 (https://arxiv.org/abs/1301.1669). Bibcode:2013ApJ...764..101B (https://ui.adsabs.harvard.edu/abs/2013ApJ...764..101B). doi:10.1088/0004-637X/764/1/101 (https://doi.org/10.1088%2F0004-637X%2F764%2F1%2F101). S2CID 118575478 (https://api.semanticscholar.org/CorpusID:118575478).
75. Clavin, Whitney; Harrington, J. D. (25 April 2014). "NASA's Spitzer and WISE Telescopes Find Close, Cold Neighbor of Sun" (http://www.nasa.gov/jpl/wise/spitzer-coldest-brown-dwarf-20140425/). *NASA.gov*. Archived (https://web.archive.org/web/20140426004939/http://www.nasa.gov/jpl/wise/spitzer-coldest-brown-dwarf-20140425) from the original on 26 April 2014.
76. Eisenhardt, Peter R. M.; Marocco, Federico; Fowler, John W.; Meisner, Aaron M.; Kirkpatrick, J. Davy; Garcia, Nelson; Jarrett, Thomas H.; Koontz, Renata; Marchese, Elijah J.; Stanford, S. Adam; Caselden, Dan (2020). "The CatWISE Preliminary Catalog: Motions from WISE and NEOWISE Data" (https://doi.org/10.3847%2F1538-4365%2Fab7f2a). *The Astrophysical Journal Supplement Series*. **247** (2): 69. arXiv:1908.08902 (https://arxiv.org/abs/1908.08902). Bibcode:2020ApJS..247...69E (https://ui.adsabs.harvard.edu/abs/2020ApJS..247...69E). doi:10.3847/1538-4365/ab7f2a (https://doi.org/10.3847%2F1538-4365%2Fab7f2a). S2CID 201645245 (https://api.semanticscholar.org/CorpusID:201645245).
77. Meisner, Aaron M.; Caselden, Dan; Kirkpatrick, J. Davy; Marocco, Federico; Gelino, Christopher R.; Cushing, Michael C.; Eisenhardt, Peter R. M.; Wright, Edward L.; Faherty, Jacqueline K.; Koontz, Renata; Marchese, Elijah J. (2020). "Expanding the Y Dwarf Census with Spitzer Follow-up of the Coldest CatWISE Solar Neighborhood Discoveries" (https://doi.org/10.3847%2F1538-4357%2Fab6215). *The Astrophysical Journal*. **889** (2): 74. arXiv:1911.12372 (https://arxiv.org/abs/1911.12372). Bibcode:2020ApJ...889...74M (https://ui.adsabs.harvard.edu/abs/2020ApJ...889...74M). doi:10.3847/1538-4357/ab6215 (https://doi.org/10.3847%2F1538-4357%2Fab6215). S2CID 208513044 (https://api.semanticscholar.org/CorpusID:208513044).

78. Marocco, Federico; Caselden, Dan; Meisner, Aaron M.; Kirkpatrick, J. Davy; Wright, Edward L.; Faherty, Jacqueline K.; Gelino, Christopher R.; Eisenhardt, Peter R. M.; Fowler, John W.; Cushing, Michael C.; Cutri, Roc M.; Garcia, Nelson; Jarrett, Thomas H.; Koontz, Renata; Mainzer, Amanda; Marchese, Elijah J.; Mobasher, Bahram; Schlegel, David J.; Stern, Daniel; Teplitz, Harry I. (2019). "CWISEP J193518.59 − 154620.3: An Extremely Cold Brown Dwarf in the Solar Neighborhood Discovered with CatWISE" (https://doi.org/10.3847%2F1538-4357%2Fab2bf0). *The Astrophysical Journal*. **881** (1): 17. arXiv:1906.08913 (https://arxiv.org/abs/1906.08913). Bibcode:2019ApJ...881...17M (https://ui.adsabs.harvard.edu/abs/2019ApJ...881...17M). doi:10.3847/1538-4357/ab2bf0 (https://doi.org/10.3847%2F1538-4357%2Fab2bf0). S2CID 195316522 (https://api.semanticscholar.org/CorpusID:195316522).
79. "NASA's Webb Finds Signs of Possible Aurorae on Isolated Brown Dwarf - NASA" (https://www.nasa.gov/missions/webb/nasas-webb-finds-signs-of-possible-aurorae-on-isolated-brown-dwarf/). 2024-01-09. Retrieved 2024-01-10.
80. Bardalez Gagliuffi, Daniella C.; Faherty, Jacqueline K.; Backyard Worlds: Planet 9 Citizen Science Collaboration; Schneider, Adam C.; Meisner, Aaron M.; Caselden, Dan; Colin, Guillaume; Goodman, Sam; Kirkpatrick, J. Davy; Kuchner, Marc J.; Gagne, Jonathan; Logsdon, Sarah E.; Burgasser, Adam J.; Allers, Katelyn N.; Debes, John H.; Wisniewski, John (January 2020). "WISE J0830+2837: the first Y dwarf from Backyard Worlds: Planet 9". *AAS*. **52**: 132.06. Bibcode:2020AAS...23513206B (https://ui.adsabs.harvard.edu/abs/2020AAS...23513206B).
81. Zahnle, Kevin J.; Marley, Mark S. (2014-12-01). "Methane, Carbon Monoxide, and Ammonia in Brown Dwarfs and Self-Luminous Giant Planets" (https://ui.adsabs.harvard.edu/abs/2014ApJ...797...41Z). *The Astrophysical Journal*. **797** (1): 41. arXiv:1408.6283 (https://arxiv.org/abs/1408.6283). Bibcode:2014ApJ...797...41Z (https://ui.adsabs.harvard.edu/abs/2014ApJ...797...41Z). doi:10.1088/0004-637X/797/1/41 (https://doi.org/10.1088%2F0004-637X%2F797%2F1%2F41). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 118509317 (https://api.semanticscholar.org/CorpusID:118509317).
82. Bardalez Gagliuffi, Daniella C.; Faherty, Jacqueline K.; Schneider, Adam C.; Meisner, Aaron; Caselden, Dan; Colin, Guillaume; Goodman, Sam; Kirkpatrick, J. Davy; Kuchner, Marc; Gagné, Jonathan; Logsdon, Sarah E.; Burgasser, Adam J.; Allers, Katelyn; Debes, John; Wisniewski, John (2020-06-01). "WISEA J083011.95+283716.0: A Missing Link Planetary-mass Object" (https://doi.org/10.3847%2F1538-4357%2Fab8d25). *The Astrophysical Journal*. **895** (2): 145. arXiv:2004.12829 (https://arxiv.org/abs/2004.12829). Bibcode:2020ApJ...895..145B (https://ui.adsabs.harvard.edu/abs/2020ApJ...895..145B). doi:10.3847/1538-4357/ab8d25 (https://doi.org/10.3847%2F1538-4357%2Fab8d25). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 216553879 (https://api.semanticscholar.org/CorpusID:216553879).
83. "Spectral type codes" (http://simbad.u-strasbg.fr/simbad/sim-display?data=sptypes). *simbad.u-strasbg.fr*. Retrieved 2020-03-06.
84. Burningham, Ben; Smith, Leigh; Cardoso, Cátia V.; Lucas, Philip W.; Burgasser, Adam J.; Jones, Hugh R. A.; Smart, Richard L. (May 2014). "The discovery of a T6.5 subdwarf". *Monthly Notices of the Royal Astronomical Society*. **440** (1): 359–364. arXiv:1401.5982 (https://arxiv.org/abs/1401.5982). Bibcode:2014MNRAS.440..359B (https://ui.adsabs.harvard.edu/abs/2014MNRAS.440..359B). doi:10.1093/mnras/stu184 (https://doi.org/10.1093%2Fmnras%2Fstu184). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 119283917 (https://api.semanticscholar.org/CorpusID:119283917).
85. Cruz, Kelle L.; Kirkpatrick, J. Davy; Burgasser, Adam J. (February 2009). "Young L Dwarfs Identified in the Field: A Preliminary Low-Gravity, Optical Spectral Sequence from L0 to L5". *The Astronomical Journal*. **137** (2): 3345–3357. arXiv:0812.0364 (https://arxiv.org/abs/0812.0364). Bibcode:2009AJ....137.3345C (https://ui.adsabs.harvard.edu/abs/2009AJ....137.3345C). doi:10.1088/0004-6256/137/2/3345 (https://doi.org/10.1088%2F0004-6256%2F137%2F2%2F3345). ISSN 0004-6256 (https://www.worldcat.org/issn/0004-6256). S2CID 15376964 (https://api.semanticscholar.org/CorpusID:15376964).
86. Looper, Dagny L.; Kirkpatrick, J. Davy; Cutri, Roc M.; Barman, Travis; Burgasser, Adam J.; Cushing, Michael C.; Roellig, Thomas; McGovern, Mark R.; McLean, Ian S.; Rice, Emily; Swift, Brandon J. (October 2008). "Discovery of Two Nearby Peculiar L Dwarfs from the 2MASS Proper-Motion Survey: Young or Metal-Rich?". *Astrophysical Journal*. **686** (1): 528–541. arXiv:0806.1059 (https://arxiv.org/abs/0806.1059). Bibcode:2008ApJ...686..528L (https://ui.adsabs.harvard.edu/abs/2008ApJ...686..528L). doi:10.1086/591025 (https://doi.org/10.1086%2F591025). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 18381182 (https://api.semanticscholar.org/CorpusID:18381182).

87. Kirkpatrick, J. Davy; Looper, Dagny L.; Burgasser, Adam J.; Schurr, Steven D.; Cutri, Roc M.; Cushing, Michael C.; Cruz, Kelle L.; Sweet, Anne C.; Knapp, Gillian R.; Barman, Travis S.; Bochanski, John J. (September 2010). "Discoveries from a Near-infrared Proper Motion Survey Using Multi-epoch Two Micron All-Sky Survey Data". *Astrophysical Journal Supplement Series*. **190** (1): 100–146. arXiv:1008.3591 (https://arxiv.org/abs/1008.3591). Bibcode:2010ApJS..190..100K (https://ui.adsabs.harvard.edu/abs/2010ApJS..190..100K). doi:10.1088/0067-0049/190/1/100 (https://doi.org/10.1088%2F0067-0049%2F190%2F1%2F100). ISSN 0067-0049 (https://www.worldcat.org/issn/0067-0049). S2CID 118435904 (https://api.semanticscholar.org/CorpusID:118435904).
88. Faherty, Jacqueline K.; Riedel, Adric R.; Cruz, Kelle L.; Gagne, Jonathan; Filippazzo, Joseph C.; Lambrides, Erini; Fica, Haley; Weinberger, Alycia; Thorstensen, John R.; Tinney, Chris G.; Baldassare, Vivienne (July 2016). "Population Properties of Brown Dwarf Analogs to Exoplanets" (https://doi.org/10.3847%2F0067-0049%2F225%2F1%2F10). *Astrophysical Journal Supplement Series*. **225** (1): 10. arXiv:1605.07927 (https://arxiv.org/abs/1605.07927). Bibcode:2016ApJS..225...10F (https://ui.adsabs.harvard.edu/abs/2016ApJS..225...10F). doi:10.3847/0067-0049/225/1/10 (https://doi.org/10.3847%2F0067-0049%2F225%2F1%2F10). ISSN 0067-0049 (https://www.worldcat.org/issn/0067-0049). S2CID 118446190 (https://api.semanticscholar.org/CorpusID:118446190).
89. Reid, Neill. "Colour-magnitude data" (http://www.stsci.edu/~inr/cmd.html). *www.stsci.edu*. Retrieved 2020-03-06.
90. National Radio Astronomy Observatory (9 April 2020). "Astronomers measure wind speed on a brown dwarf – Atmosphere, interior rotating at different speeds" (https://www.eurekalert.org/pub_releases/2020-04/nrao-amw040620.php). *EurekAlert!*. Retrieved 10 April 2020.
91. Chen, Minghan; Li, Yiting; Brandt, Timothy D.; Dupuy, Trent J.; Cardoso, Cátia V.; McCaughrean, Mark J. (2022). "Precise Dynamical Masses of ε Indi Ba and Bb: Evidence of Slowed Cooling at the L/T Transition" (https://doi.org/10.3847%2F1538-3881%2Fac66d2). *The Astronomical Journal*. **163** (6): 288. arXiv:2205.08077 (https://arxiv.org/abs/2205.08077). Bibcode:2022AJ....163..288C (https://ui.adsabs.harvard.edu/abs/2022AJ....163..288C). doi:10.3847/1538-3881/ac66d2 (https://doi.org/10.3847%2F1538-3881%2Fac66d2). S2CID 248834536 (https://api.semanticscholar.org/CorpusID:248834536).
92. "NASA Space Telescopes See Weather Patterns in Brown Dwarf" (https://web.archive.org/web/20140402162957/http://hubblesite.org/newscenter/archive/releases/star/brown-dwarf/2013/02/). *Hubblesite*. NASA. Archived from the original (http://hubblesite.org/newscenter/archive/releases/star/brown-dwarf/2013/02/) on 2 April 2014. Retrieved 8 January 2013.
93. "Astronomers Clock High Winds on Object Outside Our Solar System" (https://www.cnn.com/2020/04/09/world/brown-dwarf-wind-speed-scn/index.html). *CNN.com*. CNN. 9 April 2020. Retrieved 11 April 2020.
94. Route, Matthew; Wolszczan, Alexander (20 October 2016). "The Second Arecibo Search for 5 GHz Radio Flares from Ultracool Dwarfs" (https://doi.org/10.3847%2F0004-637X%2F830%2F2%2F85). *The Astrophysical Journal*. **830** (2): 85. arXiv:1608.02480 (https://arxiv.org/abs/1608.02480). Bibcode:2016ApJ...830...85R (https://ui.adsabs.harvard.edu/abs/2016ApJ...830...85R). doi:10.3847/0004-637X/830/2/85 (https://doi.org/10.3847%2F0004-637X%2F830%2F2%2F85). S2CID 119279978 (https://api.semanticscholar.org/CorpusID:119279978).
95. Rutledge, Robert E.; Basri, Gibor; Martín, Eduardo L.; Bildsten, Lars (1 August 2000). "Chandra Detection of an X-Ray Flare from the Brown Dwarf LP 944-20". *The Astrophysical Journal*. **538** (2): L141–L144. arXiv:astro-ph/0005559 (https://arxiv.org/abs/astro-ph/0005559). Bibcode:2000ApJ...538L.141R (https://ui.adsabs.harvard.edu/abs/2000ApJ...538L.141R). doi:10.1086/312817 (https://doi.org/10.1086%2F312817). S2CID 17800872 (https://api.semanticscholar.org/CorpusID:17800872).
96. Berger, Edo; Ball, Steven; Becker, Kate M.; Clarke, Melanie; Frail, Dale A.; Fukuda, Therese A.; Hoffman, Ian M.; Mellon, Richard; Momjian, Emmanuel; Murphy, Nathanial W.; Teng, Stacey H.; Woodruff, Timothy; Zauderer, B. Ashley; Zavala, Robert T. (2001-03-15). "Discovery of radio emission from the brown dwarf LP944-20" (https://web.archive.org/web/20210427121818/https://cds.cern.ch/record/487607). *Nature* (Submitted manuscript). **410** (6826): 338–340. arXiv:astro-ph/0102301 (https://arxiv.org/abs/astro-ph/0102301). Bibcode:2001Natur.410..338B (https://ui.adsabs.harvard.edu/abs/2001Natur.410..338B). doi:10.1038/35066514 (https://doi.org/10.1038%2F35066514). PMID 11268202 (https://pubmed.ncbi.nlm.nih.gov/11268202). S2CID 4411256 (https://api.semanticscholar.org/CorpusID:4411256). Archived from the original (https://cds.cern.ch/record/487607) on 2021-04-27.
97. Chauvin, Gael; Zuckerman, Ben; Lagrange, Anne-Marie. "Yes, it is the Image of an Exoplanet: Astronomers Confirm the First Image of a Planet Outside of Our Solar System" (https://www.eso.org/public/news/eso0515/) (Press release). European Southern Observatory. Retrieved 2020-02-09.

98. Luhman, Kevin L. (April 2013). "Discovery of a Binary Brown Dwarf at 2 pc from the Sun". *Astrophysical Journal Letters*. **767** (1): L1. arXiv:1303.2401 (https://arxiv.org/abs/1303.2401). Bibcode:2013ApJ...767L...1L (https://ui.adsabs.harvard.edu/abs/2013ApJ...767L...1L). doi:10.1088/2041-8205/767/1/L1 (https://doi.org/10.1088%2F2041-8205%2F767%2F1%2FL1). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 8419422 (https://api.semanticscholar.org/CorpusID:8419422).
99. "X-rays from a Brown Dwarf's Corona" (https://web.archive.org/web/20101230000830/http://www.williams.edu/Astronomy/jay/chapter18_etu6.html). April 14, 2003. Archived from the original (http://www.williams.edu/Astronomy/jay/chapter18_etu6.html) on December 30, 2010. Retrieved March 19, 2010.
100. Route, Matthew (10 August 2017). "Radio-flaring Ultracool Dwarf Population Synthesis" (https://doi.org/10.3847%2F1538-4357%2Faa7ede). *The Astrophysical Journal*. **845** (1): 66. arXiv:1707.02212 (https://arxiv.org/abs/1707.02212). Bibcode:2017ApJ...845...66R (https://ui.adsabs.harvard.edu/abs/2017ApJ...845...66R). doi:10.3847/1538-4357/aa7ede (https://doi.org/10.3847%2F1538-4357%2Faa7ede). S2CID 118895524 (https://api.semanticscholar.org/CorpusID:118895524).
101. Kao, Melodie M.; Hallinan, Gregg; Pineda, J. Sebastian; Stevenson, David; Burgasser, Adam J. (31 July 2018). "The Strongest Magnetic Fields on the Coolest Brown Dwarfs" (https://doi.org/10.3847%2F1538-4365%2Faac2d5). *The Astrophysical Journal Supplement Series*. **237** (2): 25. arXiv:1808.02485 (https://arxiv.org/abs/1808.02485). Bibcode:2018ApJS..237...25K (https://ui.adsabs.harvard.edu/abs/2018ApJS..237...25K). doi:10.3847/1538-4365/aac2d5 (https://doi.org/10.3847%2F1538-4365%2Faac2d5). S2CID 118898602 (https://api.semanticscholar.org/CorpusID:118898602).
102. Route, Matthew (10 July 2017). "Is WISEP J060738.65+242953.4 Really A Magnetically Active, Pole-on L Dwarf?" (https://doi.org/10.3847%2F1538-4357%2Faa78ab). *The Astrophysical Journal*. **843** (2): 115. arXiv:1706.03010 (https://arxiv.org/abs/1706.03010). Bibcode:2017ApJ...843..115R (https://ui.adsabs.harvard.edu/abs/2017ApJ...843..115R). doi:10.3847/1538-4357/aa78ab (https://doi.org/10.3847%2F1538-4357%2Faa78ab). S2CID 119056418 (https://api.semanticscholar.org/CorpusID:119056418).
103. Route, Matthew (20 October 2016). "The Discovery of Solar-like Activity Cycles Beyond the End of the Main Sequence?" (https://doi.org/10.3847%2F2041-8205%2F830%2F2%2FL27). *The Astrophysical Journal Letters*. **830** (2): L27. arXiv:1609.07761 (https://arxiv.org/abs/1609.07761). Bibcode:2016ApJ...830L..27R (https://ui.adsabs.harvard.edu/abs/2016ApJ...830L..27R). doi:10.3847/2041-8205/830/2/L27 (https://doi.org/10.3847%2F2041-8205%2F830%2F2%2FL27). S2CID 119111063 (https://api.semanticscholar.org/CorpusID:119111063).
104. Meisner, Aaron; Kocz, Amanda. "Mapping Our Sun's Backyard" (https://noirlab.edu/public/news/noirlab2105/). NOIRLab. Retrieved 1 February 2021.
105. O'Neill, Ian (12 June 2012). "Brown Dwarfs, Runts of Stellar Litter, Rarer than Thought" (http://www.space.com/16112-brown-dwarf-stars-sun-rare.html). Space.com. Retrieved 2012-12-28.
106. Muzic, Koraljka; Schoedel, Rainer; Scholz, Alexander; Geers, Vincent C.; Jayawardhana, Ray; Ascenso, Joana; Cieza, Lucas A. (2017-07-02). "The low-mass content of the massive young star cluster RCW 38". *Monthly Notices of the Royal Astronomical Society*. **471** (3): 3699–3712. arXiv:1707.00277 (https://arxiv.org/abs/1707.00277). Bibcode:2017MNRAS.471.3699M (https://ui.adsabs.harvard.edu/abs/2017MNRAS.471.3699M). doi:10.1093/mnras/stx1906 (https://doi.org/10.1093%2Fmnras%2Fstx1906). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 54736762 (https://api.semanticscholar.org/CorpusID:54736762).
107. Apai, Dániel; Karalidi, T.; Marley, Mark S.; Yang, H.; Flateau, D.; Metchev, S.; Cowan, N. B.; Buenzli, E.; Burgasser, Adam J.; Radigan, J.; Artigau, Étienne; Lowrance, P. (2017). "Zones, spots, and planetary-scale waves beating in brown dwarf atmospheres" (https://doi.org/10.1126%2Fscience.aam9848). *Science*. **357** (6352): 683–687. Bibcode:2017Sci...357..683A (https://ui.adsabs.harvard.edu/abs/2017Sci...357..683A). doi:10.1126/science.aam9848 (https://doi.org/10.1126%2Fscience.aam9848). PMID 28818943 (https://pubmed.ncbi.nlm.nih.gov/28818943).
108. Gohd, Chelsea (19 August 2020). "Volunteers spot almost 100 cold brown dwarfs near our sun" (https://www.space.com/citizen-scientists-discover-95-brown-dwarfs.html). *Space.com*.
109. info@noirlab.edu. "Are the Coolest Brown Dwarfs Loners?" (https://www.noirlab.edu/public/announcements/geminiann16003/). *www.noirlab.edu*. Retrieved 2023-04-16.
110. Fontanive, Clémence; Biller, Beth; Bonavita, Mariangela; Allers, Katelyn (2018-09-01). "Constraining the multiplicity statistics of the coolest brown dwarfs: binary fraction continues to decrease with spectral type" (https://ui.adsabs.harvard.edu/abs/2018MNRAS.479.2702F). *Monthly Notices of the Royal Astronomical Society*. **479** (2): 2702–2727. arXiv:1806.08737 (https://arxiv.org/abs/1806.08737). Bibcode:2018MNRAS.479.2702F (https://ui.adsabs.harvard.edu/abs/2018MNRAS.479.2702F). doi:10.1093/mnras/sty1682 (https://doi.org/10.1093%2Fmnras%2Fsty1682). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711).

111. Opitz, Daniela; Tinney, C. G.; Faherty, Jacqueline; Sweet, Sarah; Gelino, Christopher R.; Kirkpatrick, J. Davy (2016-02-24). "Searching for Binary Y dwarfs with the Gemini Multi-Conjugate Adaptive Optics System (GeMS)" (https://doi.org/10.3847%2F0004-637X%2F819%2F1%2F17). *The Astrophysical Journal*. **819** (1): 17. arXiv:1601.05508 (https://arxiv.org/abs/1601.05508). Bibcode:2016ApJ...819...17O (https://ui.adsabs.harvard.edu/abs/2016ApJ...819...17O). doi:10.3847/0004-637X/819/1/17 (https://doi.org/10.3847%2F0004-637X%2F819%2F1%2F17). ISSN 1538-4357 (https://www.worldcat.org/issn/1538-4357). S2CID 3208550 (https://api.semanticscholar.org/CorpusID:3208550).
112. Calissendorff, Per; De Furio, Matthew; Meyer, Michael; Albert, Loïc; Aganze, Christian; Ali-Dib, Mohamad; Gagliuffi, Daniella C. Bardalez; Baron, Frederique; Beichman, Charles A.; Burgasser, Adam J.; Cushing, Michael C.; Faherty, Jacqueline Kelly; Fontanive, Clémence; Gelino, Christopher R.; Gizis, John E. (2023-03-29). "JWST/NIRCam Discovery of the First Y+Y Brown Dwarf Binary: WISE J033605.05–014350.4" (https://doi.org/10.3847%2F2041-8213%2Facc86d). *The Astrophysical Journal Letters*. **947** (2): L30. arXiv:2303.16923 (https://arxiv.org/abs/2303.16923). Bibcode:2023ApJ...947L..30C (https://ui.adsabs.harvard.edu/abs/2023ApJ...947L..30C). doi:10.3847/2041-8213/acc86d (https://doi.org/10.3847%2F2041-8213%2Facc86d). S2CID 257833714 (https://api.semanticscholar.org/CorpusID:257833714).
113. Bouy, Hervé. "Weighing Ultra-Cool Stars - Large Ground-Based Telescopes and Hubble Team-Up to Perform First Direct Brown Dwarf Mass Measurement" (https://www.eso.org/public/news/eso0420/) (Press release). European Southern Observatory. Retrieved 2019-12-11.
114. Bouy, Hervé; Duchêne, Gaspard; Köhler, Rainer; Brandner, Wolfgang; Bouvier, Jérôme; Martín, Eduardo L.; Ghez, Andrea Mia; Delfosse, Xavier; Forveille, Thierry; Allard, France; Baraffe, Isabelle; Basri, Gibor; Close, Laird M.; McCabe, Caer E. (2004-08-01). "First determination of the dynamical mass of a binary L dwarf". *Astronomy & Astrophysics*. **423** (1): 341–352. arXiv:astro-ph/0405111 (https://arxiv.org/abs/astro-ph/0405111). Bibcode:2004A&A...423..341B (https://ui.adsabs.harvard.edu/abs/2004A&A...423..341B). doi:10.1051/0004-6361:20040551 (https://doi.org/10.1051%2F0004-6361%3A20040551). ISSN 0004-6361 (https://www.worldcat.org/issn/0004-6361). S2CID 3149721 (https://api.semanticscholar.org/CorpusID:3149721).
115. Bedin, Luigi R.; Pourbaix, Dimitri; Apai, Dániel; Burgasser, Adam J.; Buenzli, Esther; Boffin, Henri M. J.; Libralato, Mattia (2017-09-01). "Hubble Space Telescope astrometry of the closest brown dwarf binary system – I. Overview and improved orbit" (https://academic.oup.com/mnras/article/470/1/1140/3896221). *Monthly Notices of the Royal Astronomical Society*. **470** (1): 1140–1155. arXiv:1706.00657 (https://arxiv.org/abs/1706.00657). doi:10.1093/mnras/stx1177 (https://doi.org/10.1093%2Fmnras%2Fstx1177). hdl:10150/625503 (https://hdl.handle.net/10150%2F625503). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 119385778 (https://api.semanticscholar.org/CorpusID:119385778).
116. Luhman, Kevin L. (2004-10-10). "The First Discovery of a Wide Binary Brown Dwarf". *The Astrophysical Journal*. **614** (1): 398–403. arXiv:astro-ph/0407344 (https://arxiv.org/abs/astro-ph/0407344). Bibcode:2004ApJ...614..398L (https://ui.adsabs.harvard.edu/abs/2004ApJ...614..398L). doi:10.1086/423666 (https://doi.org/10.1086%2F423666). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 11733526 (https://api.semanticscholar.org/CorpusID:11733526).
117. Reipurth, Bo; Clarke, Cathie (June 2003). "Brown Dwarfs as Ejected Stellar Embryos: Observational Perspectives". *IAUS*. **211**: 13–22. arXiv:astro-ph/0209005 (https://arxiv.org/abs/astro-ph/0209005). Bibcode:2003IAUS..211...13R (https://ui.adsabs.harvard.edu/abs/2003IAUS..211...13R). doi:10.1017/s0074180900210188 (https://doi.org/10.1017%2Fs0074180900210188). ISSN 1743-9221 (https://www.worldcat.org/issn/1743-9221). S2CID 16822178 (https://api.semanticscholar.org/CorpusID:16822178).
118. Faherty, Jacqueline K.; Goodman, Sam; Caselden, Dan; Colin, Guillaume; Kuchner, Marc J.; Meisner, Aaron M.; Gagné, Jonathan; Schneider, Adam C.; Gonzales, Eileen C.; Bardalez Gagliuffi, Daniella C.; Logsdon, Sarah E. (2020). "WISE2150-7520AB: A very low mass, wide co-moving brown dwarf system discovered through the citizen science project Backyard Worlds: Planet 9" (https://doi.org/10.3847%2F1538-4357%2Fab5303). *The Astrophysical Journal*. **889** (2): 176. arXiv:1911.04600 (https://arxiv.org/abs/1911.04600). Bibcode:2020ApJ...889..176F (https://ui.adsabs.harvard.edu/abs/2020ApJ...889..176F). doi:10.3847/1538-4357/ab5303 (https://doi.org/10.3847%2F1538-4357%2Fab5303). S2CID 207863267 (https://api.semanticscholar.org/CorpusID:207863267).
119. Stassun, Keivan G.; Mathieu, Robert D.; Valenti, Jeff A. (March 2006). "Discovery of two young brown dwarfs in an eclipsing binary system". *Nature*. **440** (7082): 311–314. Bibcode:2006Natur.440..311S (https://ui.adsabs.harvard.edu/abs/2006Natur.440..311S). doi:10.1038/nature04570 (https://doi.org/10.1038%2Fnature04570). ISSN 0028-0836 (https://www.worldcat.org/issn/0028-0836). PMID 16541067 (https://pubmed.ncbi.nlm.nih.gov/16541067). S2CID 4310407 (https://api.semanticscholar.org/CorpusID:4310407).

120. Stassun, Keivan G.; Mathieu, Robert D.; Valenti, Jeff A. (2007). "A Surprising Reversal of Temperatures in the Brown-Dwarf Eclipsing Binary 2MASS J05352184-0546085". *The Astrophysical Journal*. **664** (2): 1154–1166. arXiv:0704.3106 (https://arxiv.org/abs/0704.3106). Bibcode:2007ApJ...664.1154S (https://ui.adsabs.harvard.edu/abs/2007ApJ...664.1154S). doi:10.1086/519231 (https://doi.org/10.1086%2F519231). S2CID 15144741 (https://api.semanticscholar.org/CorpusID:15144741).
121. Grether, Daniel; Lineweaver, Charles H. (2006-04-01). "How Dry is the Brown Dwarf Desert? Quantifying the Relative Number of Planets, Brown Dwarfs, and Stellar Companions around Nearby Sun-like Stars" (https://ui.adsabs.harvard.edu/abs/2006ApJ...640.1051G). *The Astrophysical Journal*. **640** (2): 1051–1062. arXiv:astro-ph/0412356 (https://arxiv.org/abs/astro-ph/0412356). Bibcode:2006ApJ...640.1051G (https://ui.adsabs.harvard.edu/abs/2006ApJ...640.1051G). doi:10.1086/500161 (https://doi.org/10.1086%2F500161). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 8563521 (https://api.semanticscholar.org/CorpusID:8563521).
122. Page, Emma; Pepper, Joshua; Kane, Stephen; Zhou, George; Addison, Brett; Wright, Duncan; Wittenmyer, Robert; Johnson, Marshall; Evans, Philip; Collins, Karen; Hellier, Coel; Jensen, Eric; Stassun, Keivan; Rodriguez, Joseph (2022-06-01). "TOI-1994b: An Eccentric Brown Dwarf Transiting a Subgiant" (https://ui.adsabs.harvard.edu/abs/2022AAS...24030521P). *American Astronomical Society Meeting Abstracts*. **54** (6): 305.21. Bibcode:2022AAS...24030521P (https://ui.adsabs.harvard.edu/abs/2022AAS...24030521P).
123. "Exoplanet Criteria for Inclusion in the Exoplanet Archive" (https://exoplanetarchive.ipac.caltech.edu/docs/exoplanet_criteria.html). *exoplanetarchive.ipac.caltech.edu*. Retrieved 2023-04-16.
124. "Working Group on Extrasolar Planets" (https://w.astro.berkeley.edu/~basri/defineplanet/IAU-WGExSP.htm). *w.astro.berkeley.edu*. Retrieved 2023-04-16.
125. Farihi, Jay; Christopher, Micol (October 2004). "A Possible Brown Dwarf Companion to the White Dwarf GD 1400". *The Astronomical Journal*. **128** (4): 1868. arXiv:astro-ph/0407036 (https://arxiv.org/abs/astro-ph/0407036). Bibcode:2004AJ....128.1868F (https://ui.adsabs.harvard.edu/abs/2004AJ....128.1868F). doi:10.1086/423919 (https://doi.org/10.1086%2F423919). ISSN 1538-3881 (https://www.worldcat.org/issn/1538-3881). S2CID 119530628 (https://api.semanticscholar.org/CorpusID:119530628).
126. Meisner, Aaron M.; Faherty, Jacqueline K.; Kirkpatrick, J. Davy; Schneider, Adam C.; Caselden, Dan; Gagné, Jonathan; Kuchner, Marc J.; Burgasser, Adam J.; Casewell, Sarah L.; Debes, John H.; Artigau, Étienne; Bardalez Gagliuffi, Daniella C.; Logsdon, Sarah E.; Kiman, Rocio; Allers, Katelyn (2020-08-01). "Spitzer Follow-up of Extremely Cold Brown Dwarfs Discovered by the Backyard Worlds: Planet 9 Citizen Science Project" (https://doi.org/10.3847%2F1538-4357%2Faba633). *The Astrophysical Journal*. **899** (2): 123. arXiv:2008.06396 (https://arxiv.org/abs/2008.06396). Bibcode:2020ApJ...899..123M (https://ui.adsabs.harvard.edu/abs/2020ApJ...899..123M). doi:10.3847/1538-4357/aba633 (https://doi.org/10.3847%2F1538-4357%2Faba633). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 221135837 (https://api.semanticscholar.org/CorpusID:221135837).
127. French, Jenni R.; Casewell, Sarah L.; Dupuy, Trent J.; Debes, John H.; Manjavacas, Elena; Martin, Emily C.; Xu, Siyi (2023-03-01). "Discovery of a resolved white dwarf-brown dwarf binary with a small projected separation: SDSS J222551.65+001637.7AB" (https://ui.adsabs.harvard.edu/abs/2023MNRAS.519.5008F). *Monthly Notices of the Royal Astronomical Society*. **519** (4): 5008–5016. arXiv:2301.02101 (https://arxiv.org/abs/2301.02101). Bibcode:2023MNRAS.519.5008F (https://ui.adsabs.harvard.edu/abs/2023MNRAS.519.5008F). doi:10.1093/mnras/stac3807 (https://doi.org/10.1093%2Fmnras%2Fstac3807). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711).
128. Leggett, S. K.; Tremblin, P.; Esplin, T. L.; Luhman, K. L.; Morley, Caroline V. (2017-06-01). "The Y-type Brown Dwarfs: Estimates of Mass and Age from New Astrometry, Homogenized Photometry, and Near-infrared Spectroscopy" (https://doi.org/10.3847%2F1538-4357%2Faa6fb5). *The Astrophysical Journal*. **842** (2): 118. arXiv:1704.03573 (https://arxiv.org/abs/1704.03573). Bibcode:2017ApJ...842..118L (https://ui.adsabs.harvard.edu/abs/2017ApJ...842..118L). doi:10.3847/1538-4357/aa6fb5 (https://doi.org/10.3847%2F1538-4357%2Faa6fb5). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 119249195 (https://api.semanticscholar.org/CorpusID:119249195).
129. Maxted, Pierre; Napiwotzki, Ralf; Dobbie, Paul; Burleigh, Matt. "A Sub-Stellar Jonah – Brown Dwarf Survives Being Swallowed" (https://www.eso.org/public/news/eso0628/) (Press release). European Southern Observatory. Retrieved 2019-12-11.
130. Casewell, Sarah L.; Braker, Ian P.; Parsons, Steven G.; Hermes, James J.; Burleigh, Matthew R.; Belardi, Claudia; Chaushev, Alexander; Finch, Nicolle L.; Roy, Mervyn; Littlefair, Stuart P.; Goad, Mike; Dennihy, Erik (31 January 2018). "The first sub-70 min non-interacting WD–BD system: EPIC212235321". *Monthly Notices of the Royal Astronomical Society*. **476** (1): 1405–1411. arXiv:1801.07773 (https://arxiv.org/abs/1801.07773). Bibcode:2018MNRAS.476.1405C (https://ui.adsabs.harvard.edu/abs/2018MNRAS.476.1405C). doi:10.1093/mnras/sty245 (https://doi.org/10.1093%2Fmnras%2Fsty245). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 55776991 (https://api.semanticscholar.org/CorpusID:55776991).

131. Longstaff, Emma S.; Casewell, Sarah L.; Wynn, Graham A.; Maxted, Pierre F. L.; Helling, Christiane (2017-10-21). "Emission lines in the atmosphere of the irradiated brown dwarf WD0137−349B" (https://academic.oup.com/mnras/article/471/2/1728/3974054). *Monthly Notices of the Royal Astronomical Society*. **471** (2): 1728–1736. arXiv:1707.05793 (https://arxiv.org/abs/1707.05793). Bibcode:2017MNRAS.471.1728L (https://ui.adsabs.harvard.edu/abs/2017MNRAS.471.1728L). doi:10.1093/mnras/stx1786 (https://doi.org/10.1093%2Fmnras%2Fstx1786). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 29792989 (https://api.semanticscholar.org/CorpusID:29792989).
132. Grether, Daniel; Lineweaver, Charles H. (April 2006). "How Dry is the Brown Dwarf Desert? Quantifying the Relative Number of Planets, Brown Dwarfs, and Stellar Companions around Nearby Sun-like Stars" (https://doi.org/10.1086%2F500161). *The Astrophysical Journal*. **640** (2): 1051–1062. arXiv:astro-ph/0412356 (https://arxiv.org/abs/astro-ph/0412356). Bibcode:2006ApJ...640.1051G (https://ui.adsabs.harvard.edu/abs/2006ApJ...640.1051G). doi:10.1086/500161 (https://doi.org/10.1086%2F500161). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
133. Rappaport, Saul A.; Vanderburg, Andrew; Nelson, Lorne; Gary, Bruce L.; Kaye, Thomas G.; Kalomeni, Belinda; Howell, Steve B.; Thorstensen, John R.; Lachapelle, François-René; Lundy, Matthew; St-Antoine, Jonathan (2017-10-11). "WD 1202-024: the shortest-period pre-cataclysmic variable" (https://academic.oup.com/mnras/article/471/1/948/3892367). *Monthly Notices of the Royal Astronomical Society*. **471** (1): 948–961. arXiv:1705.05863 (https://arxiv.org/abs/1705.05863). Bibcode:2017MNRAS.471..948R (https://ui.adsabs.harvard.edu/abs/2017MNRAS.471..948R). doi:10.1093/mnras/stx1611 (https://doi.org/10.1093%2Fmnras%2Fstx1611). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 119349942 (https://api.semanticscholar.org/CorpusID:119349942).
134. Neustroev, Vitaly V.; Mäntynen, Iikka (2023-08-01). "A brown dwarf donor and an optically thin accretion disc with a complex stream impact region in the period-bouncer candidate BW Sculptoris" (https://doi.org/10.1093%2Fmnras%2Fstad1730). *Monthly Notices of the Royal Astronomical Society*. **523** (4): 6114–6137. arXiv:2212.03264 (https://arxiv.org/abs/2212.03264). Bibcode:2023MNRAS.523.6114N (https://ui.adsabs.harvard.edu/abs/2023MNRAS.523.6114N). doi:10.1093/mnras/stad1730 (https://doi.org/10.1093%2Fmnras%2Fstad1730). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711).
135. Kato, Taichi (2015-12-01). "WZ Sge-type dwarf novae" (https://doi.org/10.1093%2Fpasj%2Fpsv077). *Publications of the Astronomical Society of Japan*. **67** (6): 108. arXiv:1507.07659 (https://arxiv.org/abs/1507.07659). Bibcode:2015PASJ...67..108K (https://ui.adsabs.harvard.edu/abs/2015PASJ...67..108K). doi:10.1093/pasj/psv077 (https://doi.org/10.1093%2Fpasj%2Fpsv077). ISSN 0004-6264 (https://www.worldcat.org/issn/0004-6264).
136. Lira, Nicolás; Blue, Charles E.; Turner, Calum; Hiramatsu, Masaaki. "When Is a Nova Not a 'Nova'? When a White Dwarf and a Brown Dwarf Collide" (https://web.archive.org/web/20191022055806/https://www.almaobservatory.org/en/press-release/when-is-a-nova-not-a-nova-when-a-white-dwarf-and-a-brown-dwarf-collide/). *ALMA Observatory*. Archived from the original (https://www.almaobservatory.org/en/press-release/when-is-a-nova-not-a-nova-when-a-white-dwarf-and-a-brown-dwarf-collide/) on 2019-10-22. Retrieved 2019-11-12.
137. Eyres, Stewart P. S.; Evans, Aneurin; Zijlstra, Albert; Avison, Adam; Gehrz, Robert D.; Hajduk, Marcin; Starrfield, Sumner; Mohamed, Shazrene; Woodward, Charles E.; Wagner, R. Mark (2018-12-21). "ALMA reveals the aftermath of a white dwarf–brown dwarf merger in CK Vulpeculae" (https://academic.oup.com/mnras/article/481/4/4931/5107360). *Monthly Notices of the Royal Astronomical Society*. **481** (4): 4931–4939. arXiv:1809.05849 (https://arxiv.org/abs/1809.05849). Bibcode:2018MNRAS.481.4931E (https://ui.adsabs.harvard.edu/abs/2018MNRAS.481.4931E). doi:10.1093/mnras/sty2554 (https://doi.org/10.1093%2Fmnras%2Fsty2554). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 119462149 (https://api.semanticscholar.org/CorpusID:119462149).
138. Swihart, Samuel J.; Strader, Jay; Chomiuk, Laura; Aydi, Elias; Sokolovsky, Kirill V.; Ray, Paul S.; Kerr, Matthew (2022-12-01). "A New Flaring Black Widow Candidate and Demographics of Black Widow Millisecond Pulsars in the Galactic Field" (https://doi.org/10.3847%2F1538-4357%2Faca2ac). *The Astrophysical Journal*. **941** (2): 199. arXiv:2210.16295 (https://arxiv.org/abs/2210.16295). Bibcode:2022ApJ...941..199S (https://ui.adsabs.harvard.edu/abs/2022ApJ...941..199S). doi:10.3847/1538-4357/aca2ac (https://doi.org/10.3847%2F1538-4357%2Faca2ac). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X).
139. Apai, Dániel; Pascucci, Ilaria; Bouwman, Jeroen; Natta, Antonella; Henning, Thomas; Dullemond, Cornelis P. (2005). "The Onset of Planet Formation in Brown Dwarf Disks". *Science*. **310** (5749): 834–6. arXiv:astro-ph/0511420 (https://arxiv.org/abs/astro-ph/0511420). Bibcode:2005Sci...310..834A (https://ui.adsabs.harvard.edu/abs/2005Sci...310..834A). doi:10.1126/science.1118042 (https://doi.org/10.1126%2Fscience.1118042). PMID 16239438 (https://pubmed.ncbi.nlm.nih.gov/16239438). S2CID 5181947 (https://api.semanticscholar.org/CorpusID:5181947).

140. Riaz, Basmah; Machida, Masahiro N.; Stamatellos, Dimitris (July 2019). "ALMA reveals a pseudo-disc in a proto-brown dwarf". *Monthly Notices of the Royal Astronomical Society*. **486** (3): 4114–4129. arXiv:1904.06418 (https://arxiv.org/abs/1904.06418). Bibcode:2019MNRAS.486.4114R (https://ui.adsabs.harvard.edu/abs/2019MNRAS.486.4114R). doi:10.1093/mnras/stz1032 (https://doi.org/10.1093%2Fmnras%2Fstz1032). ISSN 0035-8711 (https://www.worldcat.org/issn/0035-8711). S2CID 119286540 (https://api.semanticscholar.org/CorpusID:119286540).
141. Riaz, Basmah; Najita, Joan. "Punching Above Its Weight, a Brown Dwarf Launches a Parsec-Scale Jet" (https://web.archive.org/web/20200218195420/https://www.noao.edu/news/2017/pr1701.php). *National Optical Astronomy Observatory*. Archived from the original (http://www.noao.edu/news/2017/pr1701.php) on 2020-02-18. Retrieved 2020-02-18.
142. Riaz, Basmah; Briceño, Cesar; Whelan, Emma T.; Heathcote, Stephen (July 2017). "First Large-scale Herbig-Haro Jet Driven by a Proto-brown Dwarf" (https://doi.org/10.3847%2F1538-4357%2Faa70e8). *Astrophysical Journal*. **844** (1): 47. arXiv:1705.01170 (https://arxiv.org/abs/1705.01170). Bibcode:2017ApJ...844...47R (https://ui.adsabs.harvard.edu/abs/2017ApJ...844...47R). doi:10.3847/1538-4357/aa70e8 (https://doi.org/10.3847%2F1538-4357%2Faa70e8). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 119080074 (https://api.semanticscholar.org/CorpusID:119080074).
143. Burrows, Adam; Hubbard, William B.; Lunine, Jonathan I.; Liebert, James (2011). "Tidal evolution of planets around brown dwarfs". *Astronomy & Astrophysics*. **535**: A94. arXiv:1109.2906 (https://arxiv.org/abs/1109.2906). Bibcode:2011A&A...535A..94B (https://ui.adsabs.harvard.edu/abs/2011A&A...535A..94B). doi:10.1051/0004-6361/201117734 (https://doi.org/10.1051%2F0004-6361%2F201117734). S2CID 118532416 (https://api.semanticscholar.org/CorpusID:118532416).
144. Jewitt, David C., Pan-STARRS Science Overview (http://isites.harvard.edu/fs/docs/icb.topic541038.files/ay98_reading10.pdf) Archived (https://web.archive.org/web/20151016070851/http://isites.harvard.edu/fs/docs/icb.topic541038.files/ay98_reading10.pdf) 2015-10-16 at the Wayback Machine
145. Schutte, Maria (2020-08-12). "Our New Paper: Discovery of Nearby Young Brown Dwarf Disk!" (https://blog.diskdetective.org/2020/08/12/our-new-paper-discovery-of-nearby-young-brown-dwarf-disk/). *DiskDetective.org*. Retrieved 2023-09-23.
146. Schutte, Maria C.; Lawson, Kellen D.; Wisniewski, John P.; Kuchner, Marc J.; Silverberg, Steven M.; Faherty, Jacqueline K.; Gagliuffi, Daniella C. Bardalez; Kiman, Rocio; Gagné, Jonathan; Meisner, Aaron; Schneider, Adam C.; Bans, Alissa S.; Debes, John H.; Kovacevic, Natalie; Bosch, Milton K.D.; Luca, Hugo A. Durantini; Holden, Jonathan; Hyogo, Michiharu (2020-08-04). "Discovery of a Nearby Young Brown Dwarf Disk" (https://doi.org/10.3847%2F1538-3881%2Fabaccd). *The Astrophysical Journal*. **160** (4): 156. arXiv:2007.15735v2 (https://arxiv.org/abs/2007.15735v2). Bibcode:2020AJ....160..156S (https://ui.adsabs.harvard.edu/abs/2020AJ....160..156S). doi:10.3847/1538-3881/abaccd (https://doi.org/10.3847%2F1538-3881%2Fabaccd). ISSN 1538-3881 (https://www.worldcat.org/issn/1538-3881). S2CID 220920317 (https://api.semanticscholar.org/CorpusID:220920317).
147. Rilinger, Anneliese M.; Espaillat, Catherine C. (2021-11-01). "Disk Masses and Dust Evolution of Protoplanetary Disks around Brown Dwarfs" (https://doi.org/10.3847%2F1538-4357%2Fac09e5). *The Astrophysical Journal*. **921** (2): 182. arXiv:2106.05247 (https://arxiv.org/abs/2106.05247). Bibcode:2021ApJ...921..182R (https://ui.adsabs.harvard.edu/abs/2021ApJ...921..182R). doi:10.3847/1538-4357/ac09e5 (https://doi.org/10.3847%2F1538-4357%2Fac09e5). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 235377000 (https://api.semanticscholar.org/CorpusID:235377000).
148. Ricci, L.; Testi, L.; Natta, A.; Scholz, A.; de Gregorio-Monsalvo, I.; Isella, A. (2014-08-01). "Brown Dwarf Disks with ALMA" (https://ui.adsabs.harvard.edu/abs/2014ApJ...791...20R). *The Astrophysical Journal*. **791** (1): 20. arXiv:1406.0635 (https://arxiv.org/abs/1406.0635). Bibcode:2014ApJ...791...20R (https://ui.adsabs.harvard.edu/abs/2014ApJ...791...20R). doi:10.1088/0004-637X/791/1/20 (https://doi.org/10.1088%2F0004-637X%2F791%2F1%2F20). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 13180928 (https://api.semanticscholar.org/CorpusID:13180928).
149. Boucher, Anne; Lafrenière, David; Gagné, Jonathan; Malo, Lison; Faherty, Jacqueline K.; Doyon, René; Chen, Christine H. (2016-11-01). "BANYAN. VIII. New Low-mass Stars and Brown Dwarfs with Candidate Circumstellar Disks" (https://doi.org/10.3847%2F0004-637X%2F832%2F1%2F50). *The Astrophysical Journal*. **832** (1): 50. arXiv:1608.08259 (https://arxiv.org/abs/1608.08259). Bibcode:2016ApJ...832...50B (https://ui.adsabs.harvard.edu/abs/2016ApJ...832...50B). doi:10.3847/0004-637X/832/1/50 (https://doi.org/10.3847%2F0004-637X%2F832%2F1%2F50). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 119017727 (https://api.semanticscholar.org/CorpusID:119017727).

150. Silverberg, Steven M.; Wisniewski, John P.; Kuchner, Marc J.; Lawson, Kellen D.; Bans, Alissa S.; Debes, John H.; Biggs, Joseph R.; Bosch, Milton K. D.; Doll, Katharina; Luca, Hugo A. Durantini; Enachioaie, Alexandru; Hamilton, Joshua; Holden, Jonathan; Hyogo, Michiharu (2020-02-01). "Peter Pan Disks: Long-lived Accretion Disks Around Young M Stars" (https://doi.org/10.3847%2F1538-4357%2Fab68e6). *The Astrophysical Journal*. **890** (2): 106. arXiv:2001.05030 (https://arxiv.org/abs/2001.05030). Bibcode:2020ApJ...890..106S (https://ui.adsabs.harvard.edu/abs/2020ApJ...890..106S). doi:10.3847/1538-4357/ab68e6 (https://doi.org/10.3847%2F1538-4357%2Fab68e6). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 210718358 (https://api.semanticscholar.org/CorpusID:210718358).
151. Luhman, Kevin L.; Adame, Lucía; d'Alessio, Paola; Calvet, Nuria; Hartmann, Lee; Megeath, S. T.; Fazio, G. G. (2005). "Discovery of a Planetary-Mass Brown Dwarf with a Circumstellar Disk". *The Astrophysical Journal*. **635** (1): L93–L96. arXiv:astro-ph/0511807 (https://arxiv.org/abs/astro-ph/0511807). Bibcode:2005ApJ...635L..93L (https://ui.adsabs.harvard.edu/abs/2005ApJ...635L..93L). doi:10.1086/498868 (https://doi.org/10.1086%2F498868). S2CID 11685964 (https://api.semanticscholar.org/CorpusID:11685964).
152. Ricci, Luca; Testi, Leonardo; Pierce-Price, Douglas; Stoke, John. "Even Brown Dwarfs May Grow Rocky Planets" (https://web.archive.org/web/20121203042337/http://www.eso.org/public/news/eso1248/) (Press release). European Southern Observatory. Archived from the original (http://www.eso.org/public/news/eso1248/) on 3 December 2012. Retrieved 3 December 2012.
153. Lecavelier des Etangs, A.; Lissauer, Jack J. (2022-06-01). "The IAU working definition of an exoplanet" (https://ui.adsabs.harvard.edu/abs/2022NewAR..9401641L). *New Astronomy Reviews*. **94**: 101641. arXiv:2203.09520 (https://arxiv.org/abs/2203.09520). Bibcode:2022NewAR..9401641L (https://ui.adsabs.harvard.edu/abs/2022NewAR..9401641L). doi:10.1016/j.newar.2022.101641 (https://doi.org/10.1016%2Fj.newar.2022.101641). ISSN 1387-6473 (https://www.worldcat.org/issn/1387-6473). S2CID 247065421 (https://api.semanticscholar.org/CorpusID:247065421).
154. Joergens, Viki; Müller, André (2007). "16–20 MJup Radial Velocity Companion Orbiting the Brown Dwarf Candidate Cha Hα 8". *The Astrophysical Journal*. **666** (2): L113–L116. arXiv:0707.3744 (https://arxiv.org/abs/0707.3744). Bibcode:2007ApJ...666L.113J (https://ui.adsabs.harvard.edu/abs/2007ApJ...666L.113J). doi:10.1086/521825 (https://doi.org/10.1086%2F521825). S2CID 119140521 (https://api.semanticscholar.org/CorpusID:119140521).
155. Joergens, Viki; Müller, André; Reffert, Sabine (2010). "Improved radial velocity orbit of the young binary brown dwarf candidate Cha Hα 8". *Astronomy and Astrophysics*. **521** (A24): A24. arXiv:1006.2383 (https://arxiv.org/abs/1006.2383). Bibcode:2010A&A...521A..24J (https://ui.adsabs.harvard.edu/abs/2010A&A...521A..24J). doi:10.1051/0004-6361/201014853 (https://doi.org/10.1051%2F0004-6361%2F201014853). S2CID 54989533 (https://api.semanticscholar.org/CorpusID:54989533).
156. Bennet, David P.; Bond, Ian A.; Udalski, Andrzej; Sumi, Takahiro; Abe, Fumio; Fukui, Akihiko; Furusawa, Kei; Hearnshaw, John B.; Holderness, Sarah; Itow, Yoshitaka; Kamiya, Koki; Korpela, Aarno V.; Kilmartin, Pamela M.; Lin, Wei; Ling, Cho Hong; Masuda, Kimiaki; Matsubara, Yutaka; Miyake, Noriyuki; Muraki, Yasushi; Nagaya, Maiko; Okumura, Teppei; Ohnishi, Kouji; Perrott, Yvette C.; Rattenbury, Nicholas J.; Sako, Takashi; Saito, Toshiharu; Sato, S.; Skuljan, Ljiljana; Sullivan, Denis J.; Sweatman, Winston L.; Tristram, Paul J.; Yock, Philip C. M.; Kubiak, Marcin; Szymański, Michał K.; Pietrzyński, Grzegorz; Soszyński, Igor; Szewczyk, O.; Wyrzykowski, Łukasz; Ulaczyk, Krzysztof; Batista, Virginie; Beaulieu, Jean-Philippe; Brillant, Stéphane; Cassan, Arnaud; Fouqué, Pascal; Kervella, Pierre; Kubas, Daniel; Marquette, Jean-Baptiste (30 May 2008). "A Low-Mass Planet with a Possible Sub-Stellar-Mass Host in Microlensing Event MOA-2007-BLG-192". *The Astrophysical Journal*. **684** (1): 663–683. arXiv:0806.0025 (https://arxiv.org/abs/0806.0025). Bibcode:2008ApJ...684..663B (https://ui.adsabs.harvard.edu/abs/2008ApJ...684..663B). doi:10.1086/589940 (https://doi.org/10.1086%2F589940). S2CID 14467194 (https://api.semanticscholar.org/CorpusID:14467194).
157. Burrows, Adam; Hubbard, William B.; Lunine, Jonathan I.; Liebert, James (2013). "The Atomic and Molecular Content of Disks Around Very Low-mass Stars and Brown Dwarfs". *The Astrophysical Journal*. **779** (2): 178. arXiv:1311.1228 (https://arxiv.org/abs/1311.1228). Bibcode:2013ApJ...779..178P (https://ui.adsabs.harvard.edu/abs/2013ApJ...779..178P). doi:10.1088/0004-637X/779/2/178 (https://doi.org/10.1088%2F0004-637X%2F779%2F2%2F178). S2CID 119001471 (https://api.semanticscholar.org/CorpusID:119001471).
158. He, Matthias Y.; Triaud, Amaury H. M. J.; Gillon, Michaël (January 2017). "First limits on the occurrence rate of short-period planets orbiting brown dwarfs". *Monthly Notices of the Royal Astronomical Society*. **464** (3): 2687–2697. arXiv:1609.05053 (https://arxiv.org/abs/1609.05053). Bibcode:2017MNRAS.464.2687H (https://ui.adsabs.harvard.edu/abs/2017MNRAS.464.2687H). doi:10.1093/mnras/stw2391 (https://doi.org/10.1093%2Fmnras%2Fstw2391). S2CID 53692008 (https://api.semanticscholar.org/CorpusID:53692008).

159. Barnes, Rory; Heller, René (2011). "Habitable Planets Around White and Brown Dwarfs: The Perils of a Cooling Primary" (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3612282). *Astrobiology*. **13** (3): 279–291. arXiv:1211.6467 (https://arxiv.org/abs/1211.6467). Bibcode:2013AsBio..13..279B (https://ui.adsabs.harvard.edu/abs/2013AsBio..13..279B). doi:10.1089/ast.2012.0867 (https://doi.org/10.1089%2Fast.2012.0867). PMC 3612282 (https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3612282). PMID 23537137 (https://pubmed.ncbi.nlm.nih.gov/23537137).
160. Morrison, David (2 August 2011). "Scientists today no longer think an object like Nemesis could exist" (https://archive.today/20121213101422/http://astrobiology2.arc.nasa.gov/ask-an-astrobiologist/question/?id=16790). NASA Ask An Astrobiologist. Archived from the original (http://astrobiology2.arc.nasa.gov/ask-an-astrobiologist/question/?id=16790) on 13 December 2012. Retrieved 2011-10-22.
161. Comerón, F.; Neuhäuser, R.; Kaas, A. A. (2000-07-01). "Probing the brown dwarf population of the Chamaeleon I star forming region" (https://ui.adsabs.harvard.edu/abs/2000A&A...359..269C). *Astronomy and Astrophysics*. **359**: 269–288. Bibcode:2000A&A...359..269C (https://ui.adsabs.harvard.edu/abs/2000A&A...359..269C). ISSN 0004-6361 (https://www.worldcat.org/issn/0004-6361).
162. Whelan, Emma T.; Ray, Thomas P.; Bacciotti, Francesca; Natta, Antonella; Testi, Leonardo; Randich, Sofia (June 2005). "A resolved outflow of matter from a brown dwarf". *Nature*. **435** (7042): 652–654. arXiv:astro-ph/0506485 (https://arxiv.org/abs/astro-ph/0506485). Bibcode:2005Natur.435..652W (https://ui.adsabs.harvard.edu/abs/2005Natur.435..652W). doi:10.1038/nature03598 (https://doi.org/10.1038%2Fnature03598). ISSN 0028-0836 (https://www.worldcat.org/issn/0028-0836). PMID 15931217 (https://pubmed.ncbi.nlm.nih.gov/15931217). S2CID 4415442 (https://api.semanticscholar.org/CorpusID:4415442).
163. Basri, Gibor; Martín, Eduardo L. (1999). "[astro-ph/9908015] PPl 15: The First Brown Dwarf Spectroscopic Binary". *The Astronomical Journal*. **118** (5): 2460–2465. arXiv:astro-ph/9908015 (https://arxiv.org/abs/astro-ph/9908015). Bibcode:1999AJ....118.2460B (https://ui.adsabs.harvard.edu/abs/1999AJ....118.2460B). doi:10.1086/301079 (https://doi.org/10.1086%2F301079). S2CID 17662168 (https://api.semanticscholar.org/CorpusID:17662168).
164. Stassun, Keivan G; Mathieu, Robert D; Valenti, Jeff A (2006-03-16). "Discovery of two young brown dwarfs in an eclipsing binary system". *Nature*. **440** (7082): 311–314. Bibcode:2006Natur.440..311S (https://ui.adsabs.harvard.edu/abs/2006Natur.440..311S). doi:10.1038/nature04570 (https://doi.org/10.1038%2Fnature04570). PMID 16541067 (https://pubmed.ncbi.nlm.nih.gov/16541067). S2CID 4310407 (https://api.semanticscholar.org/CorpusID:4310407).
165. Scholz, Ralf-Dieter; McCaughrean, Mark (2003-01-13). "eso0303 – Discovery of Nearest Known Brown Dwarf" (https://web.archive.org/web/20081013074256/http://www.eso.org/outreach/press-rel/pr-2003/pr-01-03.html) (Press release). European Southern Observatory. Archived from the original (http://www.eso.org/outreach/press-rel/pr-2003/pr-01-03.html) on October 13, 2008. Retrieved 2013-03-16.
166. Burrows, Adam; Hubbard, William B.; Lunine, Jonathan I.; Liebert, James (2004). "A possible third component in the L dwarf binary system DENIS-P J020529.0-115925 discovered with the Hubble Space Telescope". *The Astronomical Journal*. **129** (1): 511–517. arXiv:astro-ph/0410226 (https://arxiv.org/abs/astro-ph/0410226). Bibcode:2005AJ....129..511B (https://ui.adsabs.harvard.edu/abs/2005AJ....129..511B). doi:10.1086/426559 (https://doi.org/10.1086%2F426559). S2CID 119336794 (https://api.semanticscholar.org/CorpusID:119336794).
167. Burgasser, Adam J.; Kirkpatrick, J. Davy; Burrows, Adam; Liebert, James; Reid, I. Neill; Gizis, John E.; McGovern, Mark R.; Prato, Lisa; McLean, Ian S. (2003). "The First Substellar Subdwarf? Discovery of a Metal-Poor L Dwarf with Halo Kinematics". *The Astrophysical Journal*. **592** (2): 1186–1192. arXiv:astro-ph/0304174 (https://arxiv.org/abs/astro-ph/0304174). Bibcode:2003ApJ...592.1186B (https://ui.adsabs.harvard.edu/abs/2003ApJ...592.1186B). doi:10.1086/375813 (https://doi.org/10.1086%2F375813). S2CID 11895472 (https://api.semanticscholar.org/CorpusID:11895472).
168. Wolszczan, Alexander; Route, Matthew (2014). "Timing Analysis of the Periodic Radio and Optical Brightness Variations of the Ultracool Dwarf, TVLM 513-46546". *The Astrophysical Journal*. **788** (1): 23. arXiv:1404.4682 (https://arxiv.org/abs/1404.4682). Bibcode:2014ApJ...788...23W (https://ui.adsabs.harvard.edu/abs/2014ApJ...788...23W). doi:10.1088/0004-637X/788/1/23 (https://doi.org/10.1088%2F0004-637X%2F788%2F1%2F23). S2CID 119114679 (https://api.semanticscholar.org/CorpusID:119114679).
169. Maxted, Pierre F. L.; Napiwotzki, Ralf; Dobbie, Paul D.; Burleigh, Matthew R. (2006). "Survival of a brown dwarf after engulfment by a red giant star" (https://web.archive.org/web/20210427120858/https://cds.cern.ch/record/976227). *Nature* (Submitted manuscript). **442** (7102): 543–5. arXiv:astro-ph/0608054 (https://arxiv.org/abs/astro-ph/0608054). Bibcode:2006Natur.442..543M (https://ui.adsabs.harvard.edu/abs/2006Natur.442..543M). doi:10.1038/nature04987 (https://doi.org/10.1038%2Fnature04987). hdl:2299/1227 (https://hdl.handle.net/2299%2F1227). PMID 16885979 (https://pubmed.ncbi.nlm.nih.gov/16885979). S2CID 4368344 (https://api.semanticscholar.org/CorpusID:4368344). Archived from the original (https://cds.cern.ch/record/976227) on 2021-04-27.

170. Mace, Gregory N.; Mann, Andrew W.; Skiff, Brian A.; Sneden, Christopher; Kirkpatrick, J. Davy; Schneider, Adam C.; Kidder, Benjamin; Gosnell, Natalie M.; Kim, Hwihyun; Mulligan, Brian W.; Prato, L.; Jaffe, Daniel (2018-02-01). "Wolf 1130: A Nearby Triple System Containing a Cool, Ultramassive White Dwarf" (https://doi.org/10.3847%2F1538-4357%2Faaa8dd). *The Astrophysical Journal*. **854** (2): 145. arXiv:1802.04803 (https://arxiv.org/abs/1802.04803). Bibcode:2018ApJ...854..145M (https://ui.adsabs.harvard.edu/abs/2018ApJ...854..145M). doi:10.3847/1538-4357/aaa8dd (https://doi.org/10.3847%2F1538-4357%2Faaa8dd). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 56431008 (https://api.semanticscholar.org/CorpusID:56431008).
171. Levine, Joanna L.; Steinhauer, Aaron; Elston, Richard J.; Lada, Elizabeth A. (2006-08-01). "Low-Mass Stars and Brown Dwarfs in NGC 2024: Constraints on the Substellar Mass Function" (https://ui.adsabs.harvard.edu/abs/2006ApJ...646.1215L). *The Astrophysical Journal*. **646** (2): 1215–1229. arXiv:astro-ph/0604315 (https://arxiv.org/abs/astro-ph/0604315). Bibcode:2006ApJ...646.1215L (https://ui.adsabs.harvard.edu/abs/2006ApJ...646.1215L). doi:10.1086/504964 (https://doi.org/10.1086%2F504964). ISSN 0004-637X (https://www.worldcat.org/issn/0004-637X). S2CID 118955538 (https://api.semanticscholar.org/CorpusID:118955538). "Table 3: FLMN_J0541328-0151271"
172. Zhang, ZengHua; Homeier, Derek; Pinfield, David J.; Lodieu, Nicolas; Jones, Hugh R. A.; Pavlenko, Yakiv V. (2017-06-11). "Primeval very low-mass stars and brown dwarfs – II. The most metal-poor substellar object". *Monthly Notices of the Royal Astronomical Society*. **468** (1): 261. arXiv:1702.02001 (https://arxiv.org/abs/1702.02001). Bibcode:2017MNRAS.468..261Z (https://ui.adsabs.harvard.edu/abs/2017MNRAS.468..261Z). doi:10.1093/mnras/stx350 (https://doi.org/10.1093%2Fmnras%2Fstx350). S2CID 54847595 (https://api.semanticscholar.org/CorpusID:54847595).
173. Lodieu, N.; Zapatero Osorio, M. R.; Martín, E. L.; Rebolo López, R.; Gauza, B. (2022). "Physical properties and trigonometric distance of the peculiar dwarf WISE J181005.5−101002.3". *Astronomy & Astrophysics*. **663**: A84. arXiv:2206.13097 (https://arxiv.org/abs/2206.13097). Bibcode:2022A&A...663A..84L (https://ui.adsabs.harvard.edu/abs/2022A&A...663A..84L). doi:10.1051/0004-6361/202243516 (https://doi.org/10.1051%2F0004-6361%2F202243516).
174. Tannock, Megan E.; Metchev, Stanimir; Heinze, Aren; Miles-Páez, Paulo A.; Gagné, Jonathan; Burgasser, Adam J.; Marley, Mark S.; Apai, Dániel; Suárez, Genaro; Plavchan, Peter (March 2021). "Weather on Other Worlds. V. The Three Most Rapidly Rotating Ultra-cool Dwarfs" (https://doi.org/10.3847%2F1538-3881%2Fabeb67). *The Astronomical Journal*. **161** (5): 224. arXiv:2103.01990 (https://arxiv.org/abs/2103.01990). Bibcode:2021AJ....161..224T (https://ui.adsabs.harvard.edu/abs/2021AJ....161..224T). doi:10.3847/1538-3881/abeb67 (https://doi.org/10.3847%2F1538-3881%2Fabeb67). S2CID 232105126 (https://api.semanticscholar.org/CorpusID:232105126).
175. "The Extrasolar Planet Encyclopaedia — KMT-2016-BLG-2142 b" (https://exoplanet.eu/catalog/kmt_2016_blg_2142_b--6751/). *Extrasolar Planets Encyclopaedia*. Retrieved 2021-01-12.
176. Jung, Youn Kil; Hwang, Kyu-Ha; Ryu, Yoon-Hyun; Gould, Andrew; Han, Cheongho; Yee, Jennifer C.; Albrow, Michael D.; Chung, Sun-Ju; Shin, In-Gu; Shvartzvald, Yossi; Zang, Weicheng; Cha, Sang-Mok; Kim, Dong-Jin; Kim, Hyoun-Woo; Kim, Seung-Lee (2018-11-01). "KMT-2016-BLG-1820 and KMT-2016-BLG-2142: Two Microlensing Binaries Composed of Planetary-mass Companions and Very-low-mass Primaries" (https://doi.org/10.3847%2F1538-3881%2Faae319). *The Astronomical Journal*. **156** (5): 208. arXiv:1805.09983 (https://arxiv.org/abs/1805.09983). Bibcode:2018AJ....156..208J (https://ui.adsabs.harvard.edu/abs/2018AJ....156..208J). doi:10.3847/1538-3881/aae319 (https://doi.org/10.3847%2F1538-3881%2Faae319). ISSN 0004-6256 (https://www.worldcat.org/issn/0004-6256).
177. Rose, Kovi; Pritchard, Joshua; Murphy, Tara; Caleb, Manisha; Dobie, Dougal; Driessen, Laura; Duchesne, Stefan; Kaplan, David; Lenc, Emil; Wang, Ziteng (2023). "Periodic Radio Emission from the T8 Dwarf WISE J062309.94−045624.6" (https://doi.org/10.3847%2F2041-8213%2Face188). *The Astrophysical Journal Letters*. **951** (2): L43. arXiv:2306.15219 (https://arxiv.org/abs/2306.15219). Bibcode:2023ApJ...951L..43R (https://ui.adsabs.harvard.edu/abs/2023ApJ...951L..43R). doi:10.3847/2041-8213/ace188 (https://doi.org/10.3847%2F2041-8213%2Face188). S2CID 259262475 (https://api.semanticscholar.org/CorpusID:259262475).
178. Astrobites (24 June 2020). "Transiting Brown Dwarfs from TESS 2" (https://aasnova.org/2020/06/24/transiting-brown-dwarfs-from-tess/). AAS Nova. Retrieved 2013-03-16.
179. Tannock, Megan; Metchev, Stanimir; Kocz, Amanda (7 April 2021). "Caught Speeding: Clocking the Fastest-Spinning Brown Dwarfs" (https://noirlab.edu/public/news/noirlab2114/). NOIRLab. Retrieved 9 April 2021.

External links

- HubbleSite newscenter – Weather patterns on a brown dwarf (http://hubblesite.org/newscenter/archive/releases/2013/02/image/a/)

- Allard, France; Homeier, Derek (2007). "Brown dwarfs" (https://doi.org/10.4249%2Fscholarpedia.4475). *Scholarpedia*. **2** (12): 4475. Bibcode:2007SchpJ...2.4475A (https://ui.adsabs.harvard.edu/abs/2007SchpJ...2.4475A). doi:10.4249/scholarpedia.4475 (https://doi.org/10.4249%2Fscholarpedia.4475).

History

- Kumar, Shiv S.; *Low-Luminosity Stars*. Gordon and Breach, London, 1969—an early overview paper on brown dwarfs
- The Columbia Encyclopedia: "Brown Dwarfs" (https://web.archive.org/web/20050114164835/http://www.bartleby.com/65/br/browndwa.html)

Details

- A current list of L and T dwarfs (http://www.dwarfarchives.org/)
- A geological definition of brown dwarfs (https://web.archive.org/web/20050224110208/http://astron.berkeley.edu/~stars/bdwarfs/structbd.html), contrasted with stars and planets (via Berkeley)
- I. Neill Reid's pages at the Space Telescope Science Institute:
  - On spectral analysis (https://archive.today/20121215095626/http://www-int.stsci.edu/~inr/ldwarf1.html) of M dwarfs, L dwarfs, and T dwarfs
  - Temperature and mass characteristics (https://archive.today/20130521055905/http://www-int.stsci.edu/~inr/ldwarf3.html) of low-temperature dwarfs
- First X-ray from brown dwarf observed (https://archive.today/20121206015750/http://www.spaceref.com/news/viewpr.html?pid=2192), Spaceref.com, 2000
- Montes, David; "Brown Dwarfs and ultracool dwarfs (late-M, L, T)" (http://www.ucm.es/info/Astrof/recopilaciones/enanasmarrones.html), UCM
- Wild Weather: Iron Rain on Failed Stars (http://www.space.com/scienceastronomy/060703_mystery_monday.html)—scientists are investigating astonishing weather patterns on brown dwarfs, Space.com, 2006
- NASA Brown dwarf detectives (http://www.nasa.gov/vision/universe/starsgalaxies/brown_dwarf_detectives.html) Archived (https://web.archive.org/web/20141017075014/http://www.nasa.gov/vision/universe/starsgalaxies/brown_dwarf_detectives.html) 2014-10-17 at the Wayback Machine—Detailed information in a simplified sense
- Brown Dwarfs (http://www.darkstar1.co.uk/ds3.htm)—Website with general information about brown dwarfs (has many detailed and colorful artist's impressions)

Stars

- Cha Halpha 1 (https://web.archive.org/web/20051201132115/http://ssc.spitzer.caltech.edu/documents/compendium/cha_halpha1/) stats and history
- "A census of observed brown dwarfs" (https://web.archive.org/web/20050212200244/http://astron.berkeley.edu/~stars/bdwarfs/observbd.html) (not all confirmed), 1998
- Luhman, Kevin L.; Adame, Lucía; d'Alessio, Paola; Calvet, Nuria; Hartmann, Lee; Megeath, S. Thomas; Fazio, Giovanni G. (2005). "Discovery of a Planetary-Mass Brown Dwarf with a Circumstellar Disk". *The Astrophysical Journal*. **635** (1): L93–L96. arXiv:astro-ph/0511807 (https://arxiv.org/abs/astro-ph/0511807). Bibcode:2005ApJ...635L..93L (https://ui.adsabs.harvard.edu/abs/2005ApJ...635L..93L). doi:10.1086/498868 (https://doi.org/10.1086%2F498868). S2CID 11685964 (https://api.semanticscholar.org/CorpusID:11685964).
- Michaud, Peter; Heyer, Inge; Leggett, Sandy K.; and Adamson, Andy; "Discovery Narrows the Gap Between Planets and Brown Dwarfs", Gemini and Joint Astronomy Centre, 2007 (https://web.archive.org/web/20070609130324/http://www.gemini.edu/index.php?option=content&task=view&id=232)
- Deacon, Niall R.; and Hambly, Nigel C.; "Y-Spectral class for Ultra-Cool Dwarfs", 2006 (https://arxiv.org/abs/astro-ph/0607305)

Retrieved from "https://en.wikipedia.org/w/index.php?title=Brown_dwarf&oldid=1206334997"